Natural Hazards

Assessment of flood inundation mapping of Surat city by coupled 1D/2D hydrodynamic modelling - A case application of the new HEC-RAS 5

--Manuscript Draft--

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Response to Reviewers:	The authors are thankful to the anonymous reviewers for their constructive technical comments in improving the overall quality of the paper. The paper is corrected according to the comments given and amended changes are highlighted with the red colour in the revised manuscript.

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Assessment of flood inundation mapping of Surat city by coupled 1D/2D hydrodynamic modelling – A case application of the new HEC-RAS 5

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Abstract:

Surat city of India, situated 100 km downstream of Ukai dam and 19.4 km upstream from the mouth of river Tapi has experienced the largest flood in 2006. The peak discharge of about 25,770m^3/s released from the Ukai dam was responsible for a disaster. To assess the flood and find inundation in low lying areas, simulation work is carried out under the 1D/2D couple hydrodynamic modeling. 299 cross sections, 2 hydraulic structures and 5 major bridges across the river are considered for 1D modeling, whereas a topographic map at 0.5 m contour interval was used to produce a 5 m grid and SRTM (30 & 90 m) grid has been considered for Surat and the Lower Tapi Basin. The tidal level at the river mouth and the release from the Ukai dam during 2006 flood is considered as the downstream and upstream boundaries respectively. The model is simulated under the unsteady flow condition and validated for the year 2006.The simulated result shows that 9th August was the worst day in terms of flooding for Surat city and a maximum 75-77 % area was under inundation. Out of seven zones, the West zone had the deepest flood and inundated under 4-5m. Furthermore, inundation is simulated under the bank protection work (i.e. levees, Retaining Wall) constructed after the 2006 flood. The simulated results show that the major zones are safe against the inundation under 14,430 m^3/s water releases from Ukai dam except for the West zone. The study shows the 2D capability of new HEC-RAS 5 for flood inundation mapping and management studies.

Key Words: Flood, Inundation, Levees, HEC-RAS, Lower Tapi Basin

1 Introduction

Floods are the most common and widespread disaster in a tropical country like India (Sahoo and Sreeja 2015). Intense rainfall, dense population, industrialization, illegal settlement along river banks, bank erosion, high tide and urbanization are primary causes for floods in coastal urban flood plains like Surat city(Patel and Srivastava 2013). In addition, climate change will have a key role in intensifying and accelerating the hydrological cycle, which may increase the magnitude and frequency of future floods(Kvočka et al. 2015). Floods are not fully preventable but the associated hazards could be minimized if flood prone areas are known in advance (Sahoo and Sreeja 2015). Therefore, to reduce the loss of life and property in floodplains it is necessary to predict the water levels of rivers in urban locations, including the inundation extent for the development of risk maps for insurance assessments and effective management plans for future flood risk reduction(Patel and Srivastava 2013; Timbadiya et al. 2014a). Flood inundation mapping (FIM) and identifying the flood risk zones are primary steps for formulating any flood management strategy(Sahoo and Sreeja 2015). Understanding the effects of flood inundation in terms of area, depth and time are mandatory for efficient flood risk management(Sahoo and Sreeja 2015).

Currently, many hydrodynamic models are available for 1D, 2D and 1D/2D coupled hydrodynamic modeling, which allows the simulation of different flood scenarios (Quiroga et al. 2016). Hence, numerical models are important tools for understanding flood events, flood hazard assessment and flood management planning. (Salimi et al. 2008) have integrated the Hydrologic Engineering Centre's-River Analysis System (HEC-RAS) simulation model and Geographic Information System (GIS) to get the areal extent and depth of flooding. The flood water levels along the 79km long Kalu River in Sri Lanka were simulated using the 1D HEC-RAS hydrodynamic model to reduce flood damages(Nandalal 2009). (NIH 2009) used HEC-RAS to simulate the flow in river Ganga between Buxor to Mokama to estimate the flood hazard and risk.(Masood and Takeuchi 2012) assessed the flood hazard of mid-eastern part of Greater Dhaka by developing a flood hazard map through 1D hydrodynamic simulation on the basis of a digital elevation model (DEM) data and hydrologic field-observations. (Timbadiya et al. 2014a; Timbadiya et al. 2014b) have applied successfully the 1D HEC-RAS and MIKE 11 model for prediction of stage hydrograph at lower Tapi river under the unsteady flow conditions. (ShahiriParsa et al. 2016) has studied 1D HEC-RAS and CCHE2D to assess and predict the flood depth and spatial extent of flood in the Sungai Maka floodplain, Kelantan state, Malaysia. (Khattak et al. 2016), presented the paper showing application of HEC-RAS in combination with ArcGIS, to develop floodplain maps for part of Kabul river in Pakistan. (Rahmati et al. 2016), suggested that Analytical Hierarchical Process (AHP) and GIS technique are promising for making reliable prediction on flood extent and can be used for assessment of the flood hazard potential, specifically, in data scarce regions. Although 1D modelling approaches could be useful in some contexts, mainly for artificial channels, it presents several limitations for overflow analysis (Srinivas et al. 2009). When water begins to overflow, it becomes a 2D phenomenon and the use of a2D model is more suitable.(Mignot et al. 2006) have carried out the application of 2D shallow water equation for flood modeling and mitigation planning in a dense urban area. (Carrivick 2006) has demonstrated the capability of a 2D hydrodynamic model (SOBEK) for reconstructing characteristics of a high-magnitude outburst flood and the results provide better understating of spatial and temporal hydraulics and high magnitude flow phenomena, geomorphological and sedimentological processes. (Gallegos et al. 2009) studied dam-break flood inundation of southern California using BreZo, an unstructured grid, Godunov-type, finite volume model that solves the 2D shallow-water equations. (Quiroga et al. 2016) has successfully applied the new HEC-RAS version 5 for flood hazardous assessment of the Mamore river flood and shown the 2D capability of HEC-RAS model to generate flood depth, flow velocity and flood duration. Thus, 2D numerical models have been successfully applied for flood modeling (Pathirana et al. 2011; Poretti and De Amicis 2011; Quiroga et al. 2013). A comparison of 1D, 2D, and integrated 1D–2D hydraulic models was done by (Werner 2004) and shows that integrated 1D–2D models perform better than 1D and 2D models. (Liu et al. 2015) has proposed a simple and efficient method to couple hydraulic connection between the channel and the flood detention basin and constructed coupled 1D/2D models for a real flood simulation for the Jiakouwa flood detention basin, China.

LISFLOOD-FP model developed by (Bates and De Roo 2000) has been tested to estimate the flood inundation on river reach scale,andthis consists of a one-dimensional kinematic wave approximation for channel flow solved using an explicit finite difference scheme and a two-dimensional diffusion wave representation of floodplain flow. The model was applied to a 35 km reach of the River Meuse in the Netherlands. (Syme et al. 2004)have utilized TUFLOW 2D/1D hydrodynamic flow model to simulate the floods in the Centre of Bristol, UK. (Chatterjee et al. 2008) used MIKE FLOOD to assess the effectiveness of a proposed flood emergency storage area at the middle Elbe River, Germany, in reducing the flood peaks. Recently, (Timbadiya et al. 2014a) has successfully applied the MIKE-FLOOD model for prediction of flooding stages in a Lower Tapi River (LTR) and concluded that an integrated 1D/2D model produced better results than the 1D and 2D models. For Koiliaris River, Chaina, (Vozinaki et al. 2017) demonstrated that 1D HEC-RAS and combined 1D/2D HEC-RAS simulations with 1m resolution DEM showed a better performance than the calibration and verification process of the models with 5 m resolution DEM. In addition, it was indicated that the combined 1D/2D HECRAS model performs better than the 1D HEC-RAS model for a specific study reach by using topographic data at a high spatial resolution.

Although the 1D/2D coupled hydrodynamic models have shown the capacity to reproduce flood stages and flood inundation in the aforementioned papers, more case studies around the world are still needed so that the performance and lessons with such models could be assessed and learnt, especially in developing countries where severe floods have potential to cause devastating damages. Thus, the present study has aimed to produce a 1D/2D couple hydrodynamic model for Surat city, Lower Tapi basin which is situated 100 km downstream of Ukai dam and 19.4 km upstream of mouth of river Tapi and experienced the catastrophic flood in the year of 1994, 1998 and 2006. The peak discharge of about 25,770 m^3/s released from the Ukai dam in 2006 was responsible for a disaster. During this catastrophic flood,75-77 % of various zones of Surat city was under inundation, resulting in INR 21000 crores property losses (2.9 billion Euros) and 300 people died (Patel and Srivastava 2013).Lack of flood warning information and low lying areas in Surat city caused major disaster in 2006 flood. To prevent such a flooding situation in the future and reduce the uncertainty of inundation in low lying areas, the present work is carried out using the 1D/2D couple HEC-RAS hydrodynamic modeling. Recently, the new HEC-RAS 5.0.1 has the added capability of 2D modeling along with 1D. Since HEC-RAS is freely available, it has huge potential in helping water engineers around the world in tackling flood risk problems and a case study using the latest HEC-RAS is very relevant to water engineering community. For modeling work, the release from the Ukai dam and tidal level for the flood 2006 is considered. The flood inundation, flood depth and flow velocities for the flood event 2006 is simulated. The work is validated with the observed flood depth and regional flood level maps.

2 Study area and data used

2.1 Hydrological aspect of river Tapi

Tapi river has a total length of 724 km, out of which the 214 km is in Gujarat state and it meets the Arabian Sea in the Gulf of Cambay approximately at 19.2 km west of Surat city(CWC 2000-2001).The Tapi covers an area of approximately 3837 km^2 in Gujarat state. The length of the river from the Ukai dam to the Arabian Sea is considered the Lower Tapi River (LTR) (Fig. 1), which is estimated as 122 km. The average bed slope of the river between Ukai dam to Hope Bridge is 0.00045 and upto the sea is 0.00001 (Table-1). The Lower Tapi river consists of 2 inline structures named Kakrapar weir and Singanpur weir as well as 5 major Bridges across river Tapi at Surat city (Patel and Srivastava 2013). Four major river gauge-discharge stations named Kakrapar weir, Ghala, Singanpurweir and Hope Bridge are situated on LTR (Fig. 2). The Ghala station is monitored by Central Water commission (CWC) and the others are monitored by SIC. Hope Bridge is located at Surat-Olpad-Sahol road, 103.3 km downstream of Ukai dam, which is designed for a high flood level (HFL) (GTS-RL +11.5 m). Based on the gauged data at Hope Bridge, the safe and danger level for Surat city is decided. Before the 2006 flood event, the pre-fix warning level at Hope Bridge was 8.0 m for the corresponding discharges of 11,328 m^3/s while the maximum 12.5 m water level was observed with the corresponding discharges of 25,770 m^3/s in 2006 flood (https://www.suratmunicipal.gov.in/Bridgecell/).

2.2 Surat City:

Surat city is located in Gujarat; it is known for its textile trade, diamond cutting and polishing industries, situated 100 km downstream of Ukai dam and 19.4 km upstream of the mouth of river Tapi. Surat is divided into 7 zones i.e. West zone, Central zone, North zone, East zone, South zone, South East zone and South west zone (Fig.1). Its zone boundary covers126.52 km^2 as per the SMC zone map of 2006. The Surat city is bounded by latitude 21° 06” to 21° 15” N and longitude 72 $^{\circ}$ 45” to 72 $^{\circ}$ 54” E (Fig. 1) and falls in Survey of India (SOI) map number 46C/15, 16. Surat had a population of 4.5 million in the 2011 census, making it the second largest city in the state of Gujarat, after Ahmedabad (https://en.wikipedia.org/wiki/Surat). Surat city forms an arc of a circle, the bends enclosed by its walls stretching for about a mile and a quarter along the bank of Tapi (https://www.suratmunicipal.gov.in/). From the right bank of the river, the ground rises slightly towards the north, but the height above mean sea level is 13 m. The topography is controlled by the river and is flat in general and the general slope is from north-east to south-west. Furthermore, the city can be divided into two geomorphic units namely, coastal zone and alluvial area. The coastal area represents marshy shoreline with an extensive tidal flat stretch intercepted by estuaries. Alluvial deposits from the River Tapi cover the alluvial area. The area is covered by recent alluvium of the Quaternary Age. The alluvial plain is characterized by the flood p lain of the river Tapi and river Mindhola where there is a thick alluvial cover. The alluvial plain merges into a dry, barren, sandy coastal zone. The coastal area around the river is covered by mud. The marine deposits underlie the alluvium. The alluvium consists of sand and clay layers. The climate of Surat city can be broadly divided into four seasons: Summer, Rainy, Autumn and Winter. Summer for three months from March to May, Rainy from June to September, Autumn from October and November and the Winter season is from December to February. The summers are quite hot with temperatures ranging from 37.8 $^{\circ}$C to 44.4 $^{\circ}$C. The climate is pleasant during the monsoon while autumn is temperate. The winters are not very cold but the temperatures in January range from 10 $^{\circ}$C to 15.5°C. The average annual rainfall of the city has been 1143 mm. The city has experienced the catastrophic floods in the years of 1933, 1959, 1968, 1970, 1994, 1998 and 2006. It has been estimated that the single flood event, which occurred during 7–14 August 2006, in Surat and Hazira twin-city, resulted in the deaths of 300 humans and property damage worth INR 21000 crores (Patel and Srivastava 2013). After the 2006 flood the Surat Irrigation department and SMC has carried out the embankment (levees) improvement work in and around Surat city. It is noted that a total of eight improvement schemes have been completed on the right bank whereas seven schemes have been completed at left bank side (Fig. 3). About 11,558 m and 8,700 m of bank protection work is completed on both the right and left banks of river Tapi.

Approximately, INR 125.60 crores were spent on construction of embankments against the sanction amount of 146.00 crores. In addition, flood retaining walls of 3920 m in length have been constructed downstream of Sardar bridge to Umara village, Fulpada (732 m), Ash. Samshan (130 m), Aswan Kumar (616 m), Vaidraj (171 m), Amroli R.T. wall (945 m), Utran R.T. wall (385 m) (Fig. 3), approximately 37.15 crores were spent against the sanction amount of INR 41.15 crores. The right and left bank embankments RLs have been improved significantly upto 16.55 to 21.21 m and 16.00 to 18.40 m respectively against the maximum 12.5m gauge level measured in 2006 flood. Since 2006, no major flood has been observed. However, there is a growing concern that climate change, illegal settlement along the bank of river Tapi, emergency dam releases, and uncompleted embankment work could lead to increasing flooding risk of Surat city.

2.3 Data used:

River cross-section, bank RL and distance are the major input for 1D modeling. Detailed 299 cross-sections of river Tapi showing bed and bank RL at an average interval of 150 m to 200 m, are collected from SMC and SIC, Government of Gujarat, India in AutoCAD format just after the 2006 flood (ESM_1.dwg).The sections were surveyed by Chetan Engineers, Survey and mapping consultants in May-2007 and handed over to SMC. The survey was carried out in two phases, firstly, from Singanpurweir to Ukai Dam for river sections L6A- R6A to L201-R201 with the chainage of 100.490 km. Secondly, from Singanpurweir to Arabian Sea for section LD1-RD1 to LD85 to RD 85 and with the chainage of 21.635 km. Symbols used for right bank sections are R or RD and for left bank L or LD. River Tapi steeply falls 29 m in between sections L 154 -R 154 and L 62- R 62 (Kakrapar weir to Dhoran Pardi Village) and beyond the section L 62- R 62, the river falls gradually from 5 m to 10 m near Kamrej, Kathor, Varacha, Amroli and Singanpur villages. The hourly discharge from the Ukai dam in 2006 is collected from SIC. The tidal level during the flood event is collected from Gujarat Maritime board, Gandhinagar. The discharge from Ukai dam in 2006and the tidal level are considered for upstream and downstream boundaries. The gauge and discharge data on hourly basis of Mandvi, Ghala, Singanpurweir and Hope Bridge are collected from CWC, SWDC and SIC. The flood level map prepared after 2006 flood is collected from SMC. The details of a key map of the bank protection work, details of cross-section of the earthen embankment (levees) and details of retaining wall are shown in Fig. 3, 4 (a,b) and 5 (a,b). Levees progress or completed work, top RL of left bank and right banks are collected from drainage division, SIC (Table 2)

For 2D modeling, SRTM 30 and 90 m grid interval data are downloaded from(http://earthexplorer.usgs.gov/). The Surat city including zone boundary and 0.5 m contour interval maps are collected from SMC. The digitized contours are converted into TIN and later it was converted into a 5 m x 5m grid raster format using ESRI ArcMap 10 toolbox. The river cross section, SRTM and Surat contours were interpolated together using the ordinary kriging method (ESRI ArcMap 10) to produce a high-resolution DEM (Fig. 6 (a, b)). The data were saved in Virtual Raster Translator (.vrt), Hierarchical Data Format (.hdf) and Tagged Image file (.tif) format for further use in the HEC-RAS 5.0.1.Multi-temporal satellite images, IRS P6 LISS III data of 2005–2006 periods were utilized for Land use/Land cover generation(Patel and Nandhakumar 2016). A soil map of the study area has been collected from National bureau of Soil Survey and Land Use Planning (NBSS & LUP). Topographical sheets no. 46G/3, 4, 7, 8, 11 and 12 having a 1:50,000 scales were collected from the Survey of India (SOI), Ahmedabad.

3 Modeling

This study is focused on the development of 1D/2D coupled hydrodynamic modeling for Lower Tapi Basin through new HEC-RAS 5.0.1 published by USACE. At the first stage, flood event 2006 is simulated without bank protection works and secondly, the model is run considering bank protection work with the 1D/2D unsteady flow environment. The 1D and 2D Saint Venant equation is considered in simulating both cases.

3.1 1D/2D coupled hydrodynamic modeling

The 1D HEC-RAS model is already developed so that the work is further extended in the1D/2D environment. The HEC-RAS 5.0.1 is fully solved in using the 2D Saint Venant equation (Brunner 2016b; Manual 2016; Quiroga et al. 2016):

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial x}=0 \qquad (1)$$

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)=-\frac{n^2pg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial \xi}{\partial x}+pf+\frac{\partial}{\rho\partial x}\left(h\tau_{xx}\right)+\frac{\partial}{\rho\partial y}\left(h\tau_{xy}\right) \qquad (2)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial y}\left(\frac{q^2}{h}\right)+\frac{\partial}{\partial y}\left(\frac{pq}{h}\right)=-\frac{n^2qg\sqrt{p^2+q^2}}{h^2}-gh\frac{\partial \xi}{\partial y}+qf+\frac{\partial}{\rho\partial y}\left(h\tau_{yy}\right)+\frac{\partial}{\rho\partial y}\left(h\tau_{xy}\right) \qquad (3)$$

where h is the water depth (m), p and q are the specific flow in the x an y direction ($m^2\ s^{-1}$), ξ is the surface elevation (m), g is the acceleration due to gravity (ms^{-2}), n is the Manning resistance, ρ is the water density ($kg\ m^{-3}$), τ_{xx}, τ_{yy} and τ_{xy} are the components of the effective shear stress and f is the Coriolis (s^{-1})(Quiroga et al. 2016)

Initially, a 2D computation mesh is generated for Lower Tapi basin. This computation domain is defined by a close polygon and the computation cells are aerated inside the polygon. This means that the computation mesh can be a mixture of 3, 4, 5 and maximum 8 side cells. The 90m x 90m computation point spacing is selected for LTB which generated the total 497820 grid cells. Such grid was selected in order to stay close to the original DEM (SRTM 90*90). Similar 30 m x 30 m cell spacing is selected for 2D flow area generation for LTB for DEM (SRTM 30*30) which generated the total 4484708 grid cells. The selected equations are solved with an implicit finite volume algorithm. The finite volume solution approximates the average integral on a reference volume and allows the more general approach to unstructured meshes. Hydraulic property tables are computed before starting calculations. Elevation-volume relations are computed for each cell and elevation-hydraulic properties relationships are computed for every computational cell face, similar to the cross section pre-processing in 1D. At the second stage SA/2D Area conn option is used to locate the levees and retaining wall inside the of 2D flow areas(Fig. 7).11643.58 m and 10123.94 m long levees are created on right and left bank of Tapi surrounding Surat city. 1391.11 m and 6,606.2 m long retaining wall are created on right and left bank of Tapi. After the SA/2D Area connection the 2D flow area is generated which makes 4,483,424 cells for 30 m x 30 m cell spacing for DEM (SRTM 30*30) grid. Then, the equations are solved with an iteration scheme with maximum 20 iterations with initial condition time 1 hrs and initial condition ramp up fraction 0.5. For 1D/2D coupled hydrodynamic simulation, the present study uses the two different types of boundary conditions. For 1D simulation, the release from the Ukai dam in 2006 (Flood Hydrograph) and Tidal level in the sea are considered for the upstream-downstream boundary conditions along with T.S. gate opening for Singanpurweir under the unsteady flow condition. Where as flow hydrograph (Ukai dam release) and stage hydrograph (Tidal level) is considered for upstream and downstream boundary conditions for 2D simulation. The roughness resistance was estimated based on supervised classification scheme in ERDAS IMAGINE 10. The classification of land use patterns was derived for entire Surat district including LTB and Floodplain of Surat city. The major land use/land covers were classified into 7 categories and their Manning's roughness values n assigned are for agriculture (0.07), built-up (0.2), forest (0.035), grass land/Grazing land (0.045), wastelands (0.025), wetlands (0.12) based on the suggestions by (Chow 1959; Chow et al. 1988).

In order to ensure the stability of the model, the time steps were estimated according to the Courant-Friedrichs - Lewy condition(Brunner 2016b; Manual 2016):

$$C = \frac{V\Delta T}{\Delta x} \leq 1.0 \ (With\ maximum\ C = 3.0) \tag{4}$$

Or

$$\Delta T \ \leq \frac{\Delta x}{V} \ (With\ C = 1.0) \tag{5}$$

where, C is the Courant Number, V is the flood wave velocity (m/s), ΔT computational time step(s) and Δx is the average cell size (m) (Brunner 2016b). The velocity of river flow as per the observed date is taken as 3.5 and 3.0 m/s near Hope Bridge. This value is considered for iteration in equation 5 the time steps for 90 m grid is selected 20 s and 30 m grid is selected for 10 s. The model is simulated under the unsteady flow condition and the flood inundation (depth), flood velocity, water surface elevation (WSE), arrival time, duration for each hour are obtained.

4 Results

The 2006 flood event is simulated for the time period of 5thAugust 24 hrs to 10th August 03 hrs and the model is run for total 100 hr duration. The flood depth, water surface elevation, velocity, arrival time, duration and flood inundation for seven zones are simulated. The model is simulated without bank protection work (ESM_2) and furthermore, to find the possibility of inundation in future it is also run under the bank protection (ESM_3) work like levees and retaining wall constructed after the year 2006. The other modeling parameters are considered as per the previous section. Lastly, the simulated results are validated with the regional flood level map and spatially located observed flood depth.

4.1 Flood simulation without bank protection work

The flood event 2006 is simulated under 1D/2D coupled hydrodynamic unsteady flow condition. The water depth at the simulated locations is obtained by subtracting the ground levels from the corresponding simulation levels. The outputs are taken at every 3 hr interval for flood extent (Fig. 8). A simulated result shows that on 7th Aug 03:00 hrs with the corresponding release of 10,101 m^3/s was the beginning of flood event and area near SVB bridge of Adajan and d/s of Singanpur weir, Rander of West zone were first locations to become most affected by the flood. At the same time, between 7thAug 06 hrs to 8th Aug 03 hrs the area exposed to different flood depths increases rapidly; then it remains almost constant for the west zone (Fig. 9). A total of 24.88 km^2 of the west zone was under inundation at 8^{th} Aug 09 hrs (Table 3). The discharge versus the area under inundation for various zones were calculated and shown in (Table 3). At 18:00 hrs 9^{th}Aug, 7.20 km^2 area of Central zone was inundated while for North zone inundated area was 15.21 km^2.With the same day and time constraints, 12.05 km^2 area of South zone and 18.18 km^2 area of South West zone were submerged. East zone was 11.99 km^2 under water at 15 hrs while at 21hrs, 9.31 km^2 area of South East zone was flooded. Altogether, at 18hr 9^{th} Aug, 98.75 km^2 area was inundated which was the maximum noted. In connection with percentage, 76.94% area of the city was submerged at the above said day and time (Fig. 9-11, Table 4). Surat city is located 100km^2d/s of Ukai dam and water releases from Ukai takes about 10 hrs to reach to the city. A maximum discharge of 25,770 m^3/s was released from Ukai Dam at 6:00 a.m. considering an average river velocity of3.5 m/s and 0.51 m/s in the floodplain; it may take 10-12 hrs to make the city flooded.

In West zone, Shinganpur weir, Rander, Usmani park, Choksiwwadi, Yoginagar and Adajan areas were 4-5 m submerged (Fig. 11).While in central part of West zone, Pankaj nagar, Jogini nagar, Deepmala soc, madevnagar are flooded by 3-4 m. In Cenral zone, area surrounding Sindhiwad was 3-4 m under water. Katargam and naliyasheri were 1-2 m flooded. Major East zone was flooded by 0-1m water while north zone and Ishwar nagar soc was by 3-4 m. South west zone was 1-4 m, South Zone was 1-3 m while South east zone was moderately flooded. Fig. 12 shows the water surface elevation of various zones on 9^{th} august 18:00 hrs. Velocity of water is marked 0.51 m/s in west zone from Singanpurweir to in downstream at Sardar bridge, whereas at upstream maximum velocity was 1m/s. In South, South east, south west, east and north zones maximum velocity observed was 0.51 m/s (Fig. 13). Looking to lower velocity in major part of flood prone area, water was retained and affected the people and their valuables significantly.

Fig. 14 shows that the amount of time an area is inundated as percentage of the total simulation time period (Brunner 2016a). The figure also signifies the flood propagation; the cells with higher percentage are also the first ones to get flooded. The west zone has the highest percentage time so it inundates more compared to the North zone, South westzone and South east zone. The range of inundation starts from 20% up to 70 %. It shows that West zone is under inundation up to 70 hrs. It means that the people residing in this area are difficult to evacuate during flood time.

Fig. 15 shows the arrival time in hours from a specified time in the simulation when the water depth reaches a specified inundation depth (threshold) (Brunner 2016a). In this study, the arrival time is derived at different flood inundation depths. For 2 m flood depth, the arrival time is bifurcated from 0 to maximum 96 hr as per the water released from the Ukai dam. Water achieves 2 m depth in major portion of the west zone in 30 to 40 hr, whereas for the central zone, south west zone and south east zone it takes 60 to 70 hrs to get flooded. The north zone has a similar case as the west zone; it gets flooded in 30 to 40 hr. The South zone and few portions of the east zone has the least chance to be affected by flooding and the water takes 90-96 hr to reach up to 2m depth. Hence, there is an enough time to evacuate the people from the low lying areas. Similarly, the results show the time to arrive at particular places for a water depth of 2.5m, 3m, 3.5 m, 4m, 4.5m, 5m, 5.5 m and 6m (Fig. 15).

Fig. 16 shows the duration in hours for which water depth exceeds a specified flood depth (threshold). RAS has ignored multiple peaked events. Once a depth threshold is reached the duration continues until the depth has completely receded for the event(Brunner 2016a). The duration has an inverse relation with the arrival time. Arrival time that will reduce the duration of flood water at specific depth will be intensified. The duration of flood water at depth of 2 m for west zone is 60-70 hr which shows that the flood water was retained more in West zone compared to the South zone and East zone. Whereas, a major portion of the North zone hasa duration of 65-70 hr at depth of 2 m. The details of flood inundation with various depth and duration are shown in Fig. 16.

It has been seen from the analysis and observed map, the West zone and North zone are low lying areas and were significantly affected by the 2006 flood. The curve for submerge area versus release from the dam is very steep for West zone and North zone. The 84 % area of West zone was under inundation at the discharge of 10101 m^3/s released from the Ukai, while for Central zone, North zone, East zone, South west zone and South zone, South East zone, figures are 9.44 %, 26.16 %, 0.27 %, 10% and 0% respectively.

Overall, 75-77 % area of Surat city was under water in flood 2006. It has a chance to inundate various zones more in a future flood event. In addition, it has been noted that the after 2006 flood, SIC has started to improve the bank protection work along the left and right bank of river Tapi. To check the possibility of future flood and inundation of different zones under the same release conditions, the same flood event has been simulated under the bank protection work (levees and retaining wall), which is described in the subsequent section.

4.2 Sensitivity analysis of 1D/2D modeling

For 1D flow validation, the simulated river flow at Hope Bridge is compared with the observed stages at 2006 flood. It shows that the simulated stages at Manning's 'n' 0.025 are best matched with the observed values, the R^2 value is 0.937 (Fig. 17, 18). Furthermore, the validation is also carried out for the flood plain. The observed and simulated flood depths at various locations are compared. The accuracy of the validation is dependent on the precision of contours. Present DEM of Surat city has been generated from 0.5 m contour interval with 5 m x 5 m grid. It is observed that at 9th August 18 hrs the Surat city was under the maximum inundation. The depths obtained at various zones at this time period are considered for validation. The survey was carried out for the west zone and central zone with help of Differential Geographical Positioning System (DGPS) and Electronic Distance Measurement (EDM). The location map of the observed points is shown in Fig. 19, whereas Fig. 20 shows photographs of High Flood Level (HFL) at different places on 8th and 9th August 2006. The flood inundation is validated by two different approaches. In the first approach, the simulated depths are compared with the observed photograph for various places. It has been seen that the Paradise apartment and circuit house situated in Central zone were having observed depth of 1.55 m and 0.85 m respectively. The same place fall under the depth of 0-1 and 1-2 m in flood depth map. It shows the results are promising and prove the sensitivity of 1D/2D modeling. Similarly, the observed flood depth at Parshvnagar Apartment, Sargam Complex, LIC Complex and Ascon Plaza is also compared with the simulated depth and shows the good correlation (Fig. 19 and 20). At the second stage, the simulated flood depth is compared with the observed flood level maps (Fig. 20 and 21) prepared by the SMC after 2006 flood. It has been seen that the Paradise apartment and circuit house fall under the blue color which shows the level of 3-5 ft (0.91 – 1.52 m), which indicates the good correlation with the observed depth and hence results can be used for flood mitigation analysis. However, the acquired observed points are not enough to validate the entire simulated depth map, hence more survey points and research fund is needed for better validation.

4.3 Flood simulation with the bank protection work

As described in an earlier section the major flood protection work (embankments-levees, flood retaining wall) was constructed along the left and right banks of river Tapi after 2006. After its construction, it was noted that no major floods were subsequently observed in Surat city. It is estimated that the Surat city is safe against the discharge of 16,990 m^3/s (As per the expert from SIC). To check the possibility of inundation at various discharge releases from the Ukai dam, the entire modeling is simulated under the bank protection work. The modeling parameter has been considered as described in the modeling section.

As described earlier the water takes 10-12 hrs to make the city flooded. If the same discharge was released from the Ukai dam in future considering the same stages, then the simulated result shows the Surat city will be under inundation for 24.22, 2.08, 0.19, 0.26, 0.0, 3.71, 0.0 km^2areas of West, Central, North, East, South, South West and South East zone respectively for the corresponding release of 14,430 m^3/s from Ukai dam. The simulated results show that the west zone has the maximum chance to get flooded in such a future flood event due to uncompleted bank protection work at d/s of SVP bridges, whereas the North zone is safe. The comparison of areas under inundation and in percentage with and without levees is shown in (Fig. 22; Table 3 and 4).

5 Discussions

Considering the limitation of 1D hydrodynamic modeling described earlier, a few additional limitations should be considered for 1D/2D couple hydrodynamic modeling.

1) It is assumed that the hydrological processes like infiltration, evaporation and precipitation directly on the river are small and are assumed to be neglected. Although the dry soil and heavy precipitation at LTB can affect the simulation results.
2) It is assumed that the levees and retaining walls existed as per the key map provided by the SIC, but no levees or retaining wall are observed at d/s of SVP bridge (Fig. 21 (a, b)). In addition, many places at d/s of SVP Bridge, the compound wall is considered as flood retaining wall. In this condition, the simulated results may affect significantly which confirms additional protected city than the actual.
3) The bank protection work located in HEC-RAS model is based on Google earth image and expert advice. Although a GPS survey is required to find the actual length and position of flood retaining structures.
4) In present HEC-RAS cannot be used for modeling bridges in 2D flow area due to unavailable tool. In this condition, 2D model is simulated without any hydraulic structures across the Tapi River.
5) For 2D modeling, the river DEM is generated from sections collected after 2006 flood. After one decade, the bed RL of few sections may be changed which could affect the velocity of the flow and arrival time.
6) Fig. 21 (c) shows the society in West zone, which is situated just d/s of the earthen embankment. In reality, it affects the velocity of flow in 2D, and in the result, it affects the hydraulic simulation.
7) LU/LC is produced by the help of IRS P6 LISS III data of 2005–2006 periods; it has significant chances to change the LU/LC in the last decade which will affect the roughness coefficient (‘n’) of the floodplain. In this condition, it will affect depth, duration, velocity, recession and arrival time of the flood.
8) Aggradational and degradational features and the related its time series analysis for flood inundation mapping are not performed in this research because none of the stations are available at D/S of Ukai dam on

sedimentation. Ghala is the only station which measures the discharge and water quality data. Under this condition the 1D/2D model is executed without the simulation of sediment transport.

6 Conclusions

The study has explored the applicability of the new HEC-RAS version 5.0.1 for flood inundation analysis in a 1D/2D environment. It is an applicable tool for decision makers to explore in advance the possibility of flood velocity, depth, arrival time, recession and duration at as pecific location in flood plain. Through the simulated results, the decision makers will take the appropriate decision in precise time to reduce the death toll and property losses. The salient research finding is summarized herewith from the 1D/2D couple hydrodynamic modeling:

1) It is identified that the HEC-RAS simulation time depends on 2D flow area computation, levees cell spacing and computation interval. Through the trial and error method, it is identified that the optimum computation setting are: point spacing 50 x 50 m, levees cell spacing 50 x 50 m and computation interval of 15 sec. The entire simulation under unsteady flow condition runs in 16 hr. The system used for simulation has Intel (R) core (TM) i3-4005U CPU 1.70GHz, 4GB RAM, 64-bit OS. Further decrease in grid size will increase the run time up to 3-3.5 days.

2) West zone is the low laying area in Surat city; the discharge versus submergences curve for West zone is steep and it has high chances to inundate in a future flood of the similar size to the 2006 flood. Flood rescue process for this zone must be started first to reduce the death ratio.

3) It is identified that the present literature lacks the study of flood inundation with levees structure which leads to in adequacy. To increase the realism for future flood inundation, 1D/2D hydrodynamic model is simulated considering the levees. Results show significant effect of levees on flood inundation areas. In present, the North zone is safe against the discharge of 14158 m^3/s.

4) The study shows that the West margin of the river Tapi is the most hazardous one; it has bigger flood extent, deeper flood depths, and longer flood duration. In flooded areas, the water has a velocity lower than 0.50 m/s.

5) It has been noted that the levee at right bank between the Singanpurweir and Hope Bridge is situated approximately 180 m away from the bank of the Tapi river (Fig. 22), so that the slum pockets (area of 3,65,525 m^2) and river front situated in between can't be protected through levee structure, hence has maximum probability to affect through small flood (8,495 m^3/s).

6) In 1D modeling, comparison of river Tapi stages at Hope bridge with and without Tidal wave conditions are nearer while in 1D/2D modeling the simulated stage is quite high which means stages are affected by Tidal waves or flood plain roughness's. It needs more investigation for accurate modeling.

6) It is a prime requirement to reduce the data deficiencies at Lower Tapi Basin. In future, appropriate DGPS and precise hydraulic and the hydrologic survey will reduce the uncertainty for 1D/2D couple hydrodynamic modeling.

7) Presently, at 14,429.68m^3/s , major zones of Suart city are safe against flood inundation. If water rises and accelerates gradually then the same inundation conditions will be followed as in 2006. It shows that present levees are not enough to fully protect the Surat city against 25,770 m^3/s release from Ukai. It is a

prime requirement to develop the Advance flood forecasting and Warning system for Suart city along with structural measures.

8) It is necessary to develop the center of excellence for climate change and flood mitigation analysis, which in future provides the common platform to the young researchers to compare the modeling work for the same case study. In a nutshell, it will remove the uncertainty and help to produce potential 1D/2D coupled flood modeling to apply for similar cases of the coastal urban flood in the world.

This study provides strong supportive evidence of the potentiality of new HEC-RAS 5.0.1 for flood inundation modeling. The assessment of the HEC-RAS with respect to this peculiar aspect is an important step for successful and improved development of the hydrodynamic model and thus can provide important assistance in building flood mitigation strategies for any similar cased worldwide. The study will also provide guidance to the authorities for significant dam operation and expansion of levees in future.

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Conflict of Interest

First author has received the International Travel Support (ITS) under the 'Young Scientist' programme from Science and Engineering Research Board (SERB), Department of Science and Technology (DST) for attending the international conference. Grant no SB/ITS-Y/02883/13-14.

References

Bates PD, De Roo A (2000) A simple raster-based model for flood inundation simulation Journal of hydrology 236:54-77

Brunner GW (2016a) 2D Modeling User's Manual. US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, http://www.hec.usace.army.mil/misc/files/ras/HEC-RAS5.02DModelingUsersManual.pdf.pdf,

Brunner GW (2016b) Combained 1D and 2D Modeling with HEC-RAS. US Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center, http://www.hec.usace.army.mil/misc/files/ras/Combined_1D_and_2D_Modeling_with_HEC-RAS.pdf,

Carrivick JL (2006) Application of 2D hydrodynamic modelling to high-magnitude outburst floods: an example from Kverkfjöll, Iceland Journal of hydrology 321:187-199

Chatterjee C, Foerster S, Bronstert A (2008) Comparison of hydrodynamic models of different complexities to model floods with emergency storage areas Hydrological Processes 22:4695-4709

Chow VT (1959) Open-channel hydraulics, McGraw-Hill, New York

Chow VT, Maidment DR, Mays LW (1988) Applied hydrology, McGraw-Hill, New York.

CWC (2000-2001) Water Year Book 2000-2001, Tapi basin, hydrological observation circle, Gandhinagar, Gujarat, India

Gallegos HA, Schubert JE, Sanders BF (2009) Two-dimensional, high-resolution modeling of urban dam-break flooding: A case study of Baldwin Hills, California Advances in Water Resources 32:1323-1335

http://earthexplorer.usgs.gov/

https://www.suratmunicipal.gov.in/

https://www.suratmunicipal.gov.in/Bridgecell/

Khattak MS, Anwar F, Saeed TU, Sharif M, Sheraz K, Ahmed A (2016) Floodplain mapping using HEC-RAS and ArcGIS: a case study of Kabul River Arabian Journal for Science and Engineering 41:1375-1390

Kvočka D, Falconer RA, Bray M (2015) Appropriate model use for predicting elevations and inundation extent for extreme flood events Natural Hazards 79:1791-1808

Liu Q, Qin Y, Zhang Y, Li Z (2015) A coupled 1D–2D hydrodynamic model for flood simulation in flood detention basin Natural Hazards 75:1303-1325

Manual H-R (2016) Hydrologic Engineering Center US Army Corps of Engineers

Masood M, Takeuchi K (2012) Assessment of flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model Natural Hazards 61:757-770

Mignot E, Paquier A, Haider S (2006) Modeling floods in a dense urban area using 2D shallow water equations Journal of hydrology 327:186-199

Nandalal K (2009) Use of a hydrodynamic model to forecast floods of Kalu River in Sri Lanka Journal of Flood Risk Management 2:151-158

NIH (2009) Flood hazard mapping and flood risk zoning for a River Reach (Ganga between Buxor to Hathidah (Rajendra Bridge near Mokama). National Institute of Hydrology, Roorkee

Patel DP, Nandhakumar N (2016) Runoff potential estimation of Anjana Khadi Watershed using SWAT model in the part of lower Tapi Basin, West India Sustainable Water Resources Management 2:103-118

Patel DP, Srivastava PK (2013) Flood hazards mitigation analysis using remote sensing and GIS: correspondence with town planning scheme Water resources management 27:2353-2368

Pathirana A, Tsegaye S, Gersonius B, Vairavamoorthy K (2011) A simple 2-D inundation model for incorporating flood damage in urban drainage planning Hydrology and earth system sciences 15:2747-2761

Poretti I, De Amicis M (2011) An approach for flood hazard modelling and mapping in the medium Valtellina Nat Hazards Earth Syst Sci 11:1141-1151

Quiroga VM, Kure S, Udo K, Mano A (2016) Application of 2D numerical simulation for the analysis of the February 2014 Bolivian Amazonia flood: Application of the new HEC-RAS version 5 RIBAGUA-Revista Iberoamericana del Agua 3:25-33

Quiroga VM, Popescu I, Solomatine D, Bociort L (2013) Cloud and cluster computing in uncertainty analysis of integrated flood models Journal of Hydroinformatics 15:55-70

Rahmati O, Zeinivand H, Besharat M (2016) Flood hazard zoning in Yasooj region, Iran, using GIS and multi-criteria decision analysis Geomatics, Natural Hazards and Risk 7:1000-1017

Sahoo SN, Sreeja P (2015) Development of Flood Inundation Maps and Quantification of Flood Risk in an Urban Catchment of Brahmaputra River ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering:A4015001

Salimi S, Ghanbarpour MR, Solaimani K, Ahmadi MZ (2008) Floodplain mapping using hydraulic simulation model in GIS Journal of Applied Sciences 8:660-665

ShahiriParsa A, Noori M, Heydari M, Rashidi M (2016) Floodplain Zoning Simulation by Using HEC-RAS and CCHE2D Models in the Sungai Maka River Air, Soil and Water Research 9:55

Srinivas K, Werner M, Wright N (2009) Comparing forecast skill of inundation models of differing complexity: The case of Upton upon Severn

Syme W, Pinnell M, Wicks J Modelling flood inundation of urban areas in the UK using 2D/1D hydraulic models. In: Proceedings of 8th national conference on hydraulics in water engineering. The Institution of Engineers, Australia, 2004.

Timbadiya P, Patel P, Porey P (2014a) A 1D–2D Coupled Hydrodynamic Model for River Flood Prediction in a Coastal Urban Floodplain Journal of Hydrologic Engineering 20:05014017

Timbadiya P, Patel P, Porey P (2014b) One-dimensional hydrodynamic modelling of flooding and stage hydrographs in the lower Tapi River in India Current Science 105:708-716

Vozinaki A-EK, Morianou GG, Alexakis DD, Tsanis IK (2017) Comparing 1D and combined 1D/2D hydraulic simulations using high-resolution topographic data: a case study of the Koiliaris basin, Greece Hydrological Sciences Journal 62:642-656

Werner M (2004) A comparison of flood extent modelling approaches through constraining uncertainties on gauge data Hydrol Earth Syst Sci, 8, 1141-1152, 2004

Appendix

The following symbols are used in this paper:

C	= Courant Number,
d/s	= Downstrem
f	= Coriolis (s^{-1})
g	= acceleration due to gravity (ms^{-2});
h	= water depth (m);
L	= left bank (U/S of Singanpur weir);
LD	= left bank (D/S of Singanpur weir);
n	= Manning's roughness coefficient;
p and q	= Flow in the x an y direction ($m^2\ s^{-1}$),
Q	= discharge;
R	= right bank (U/S of Singanpur weir);
RD	= right bank (D/S of Singanpur weir);
u/s	= Upstrem
ΔT	= Computational time step(s)
V	= flood wave velocity (m/s),
Δx	= average cell size (m
ξ	= Surface elevation (m),
ρ	= water density (kg m^{-3}),
τ_{xx}, τ_{yy} and τ_{xy}	= components of the effective shear stress

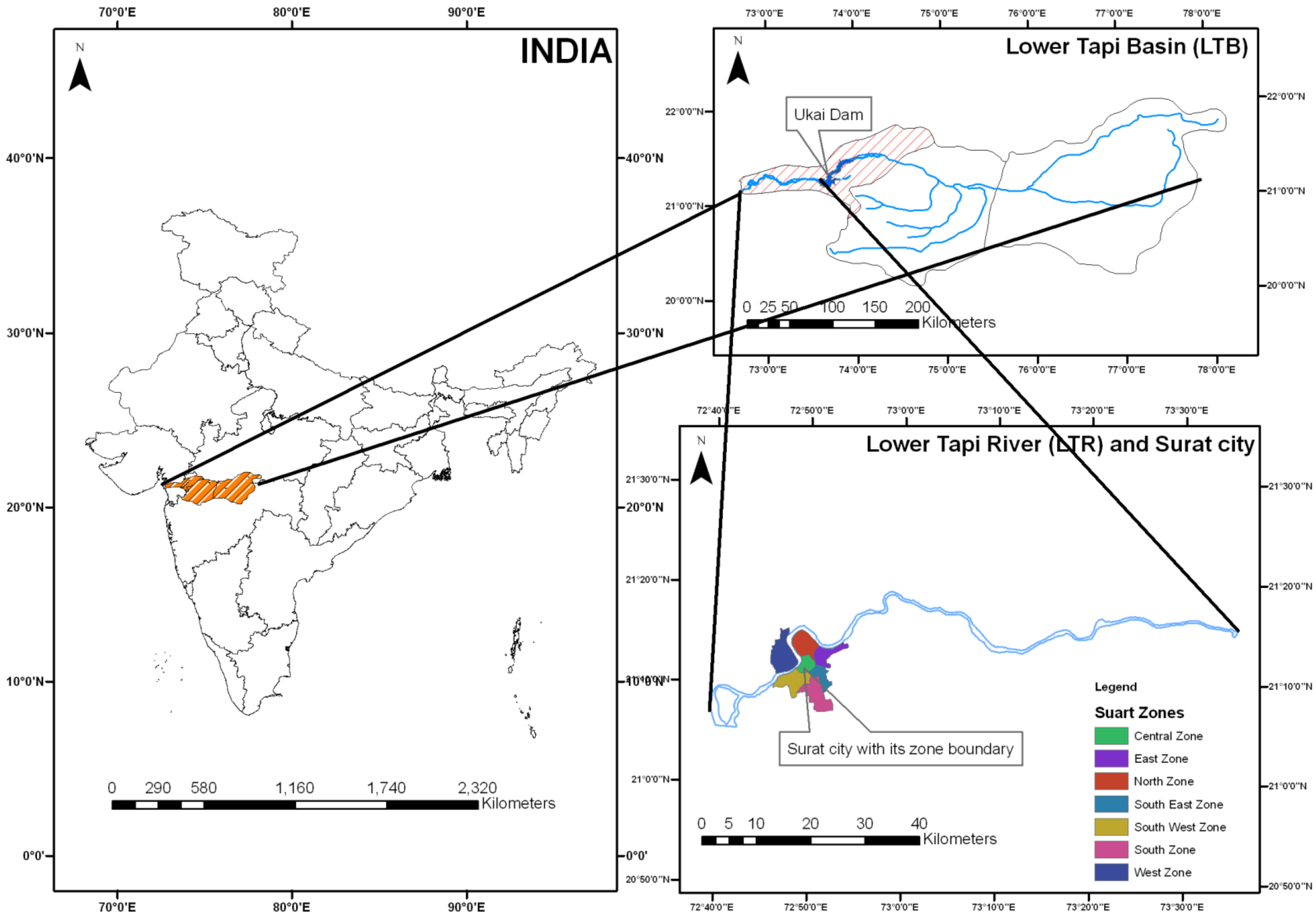


Fig.1 Location of Tapi Basin, Lower Tapi basin, and Lower Tapi river with Surat city.

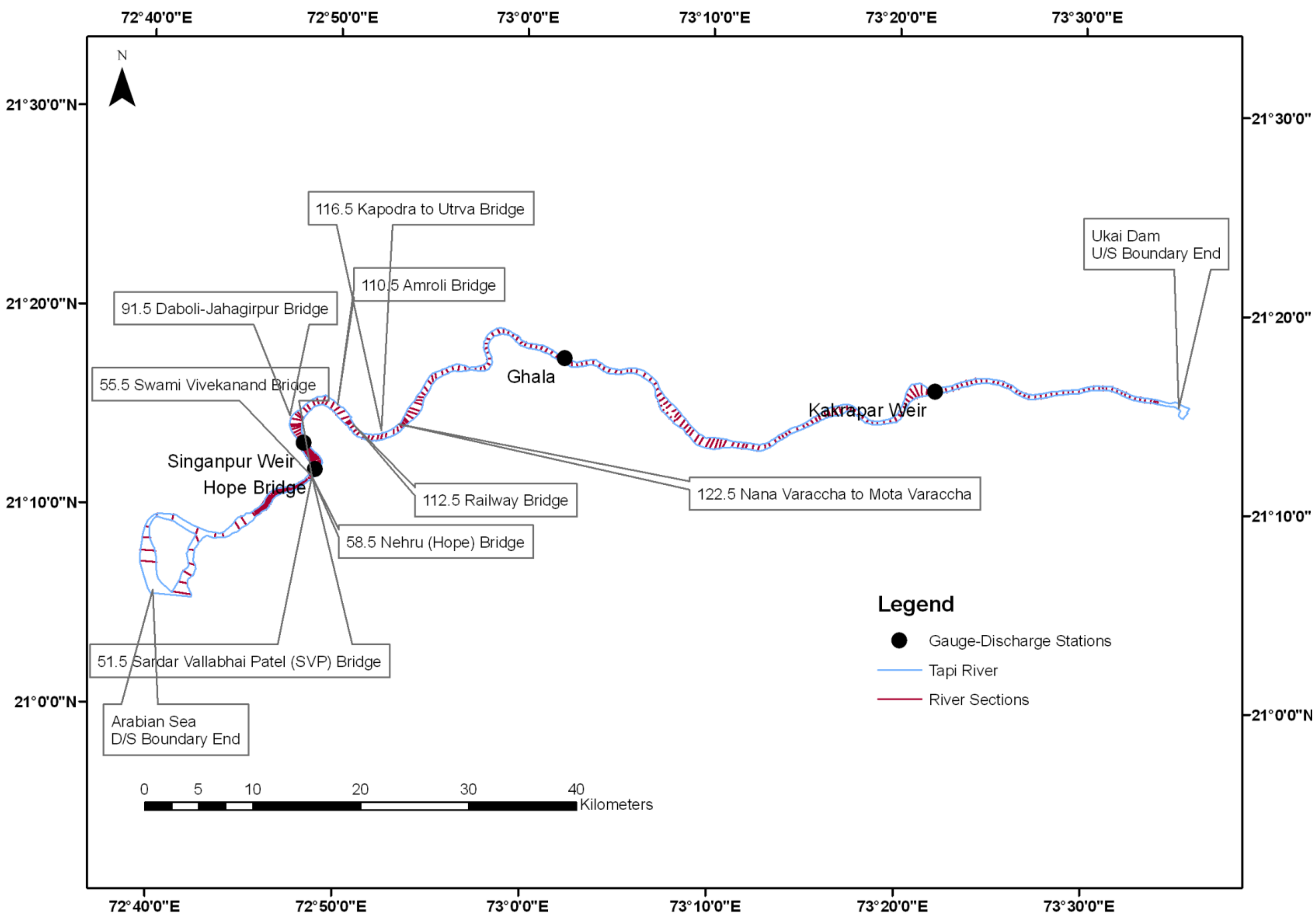


Fig.2 Lower Tapi river with Inline structure, gauge-discharge stations and bridges.

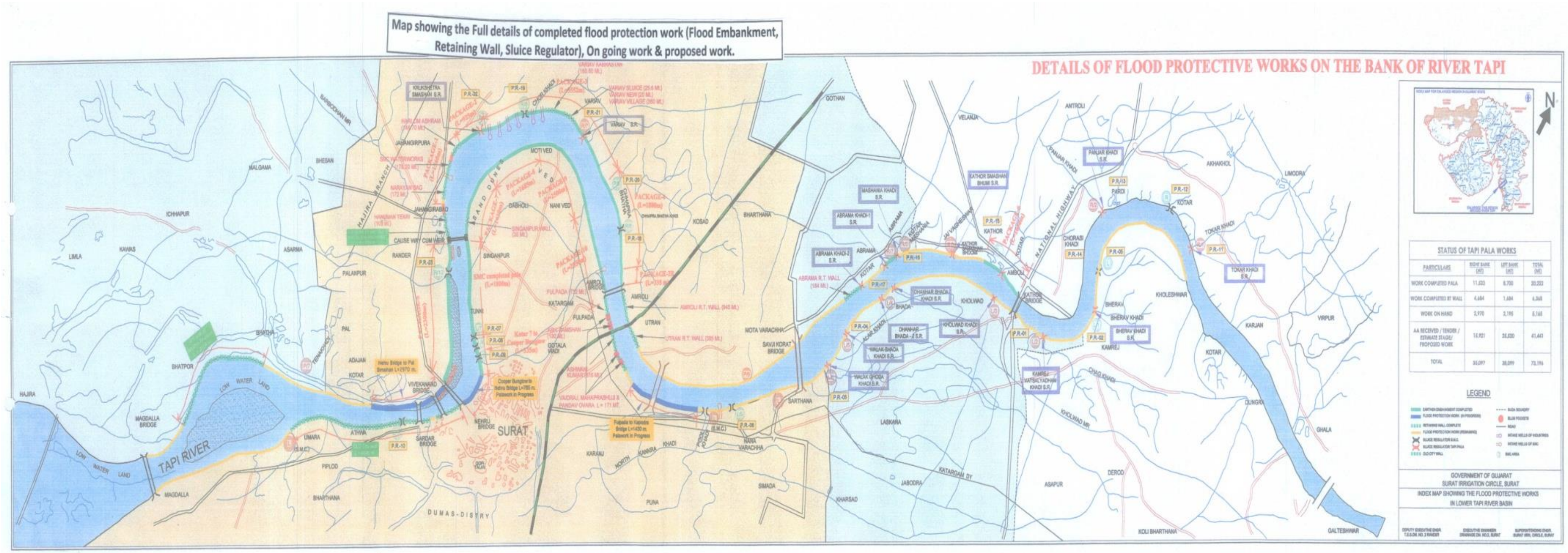
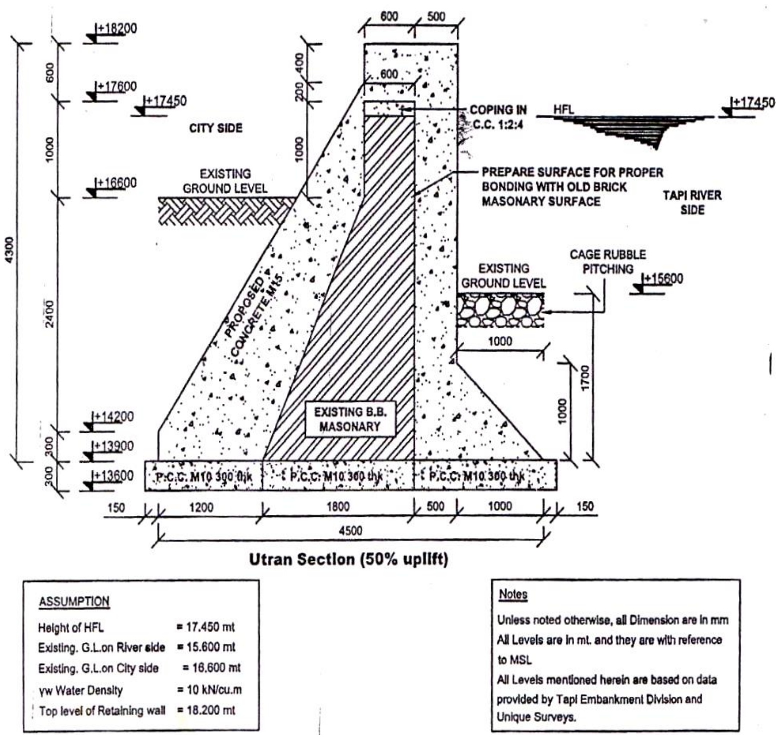


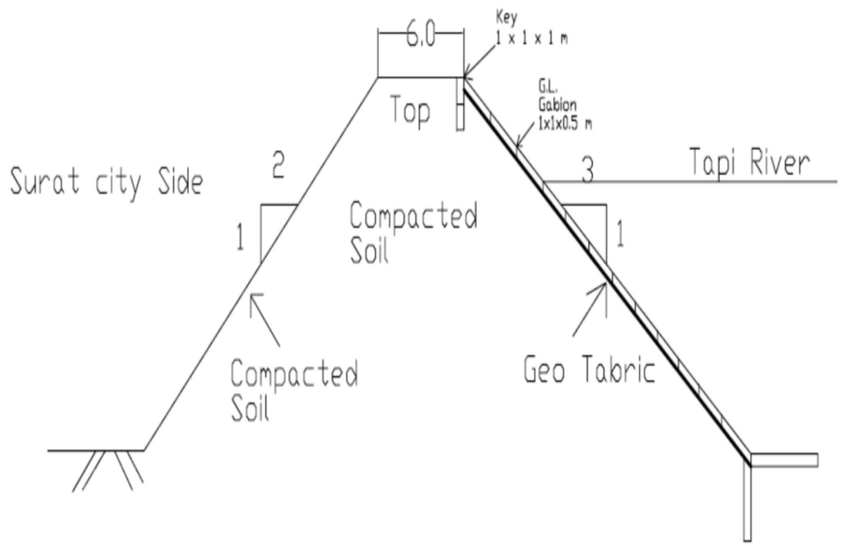
Fig. 3 Key map of Tapi bank protection work (Source: Surat Irrigation Circle (SIC), 2016)



(a)

(b)

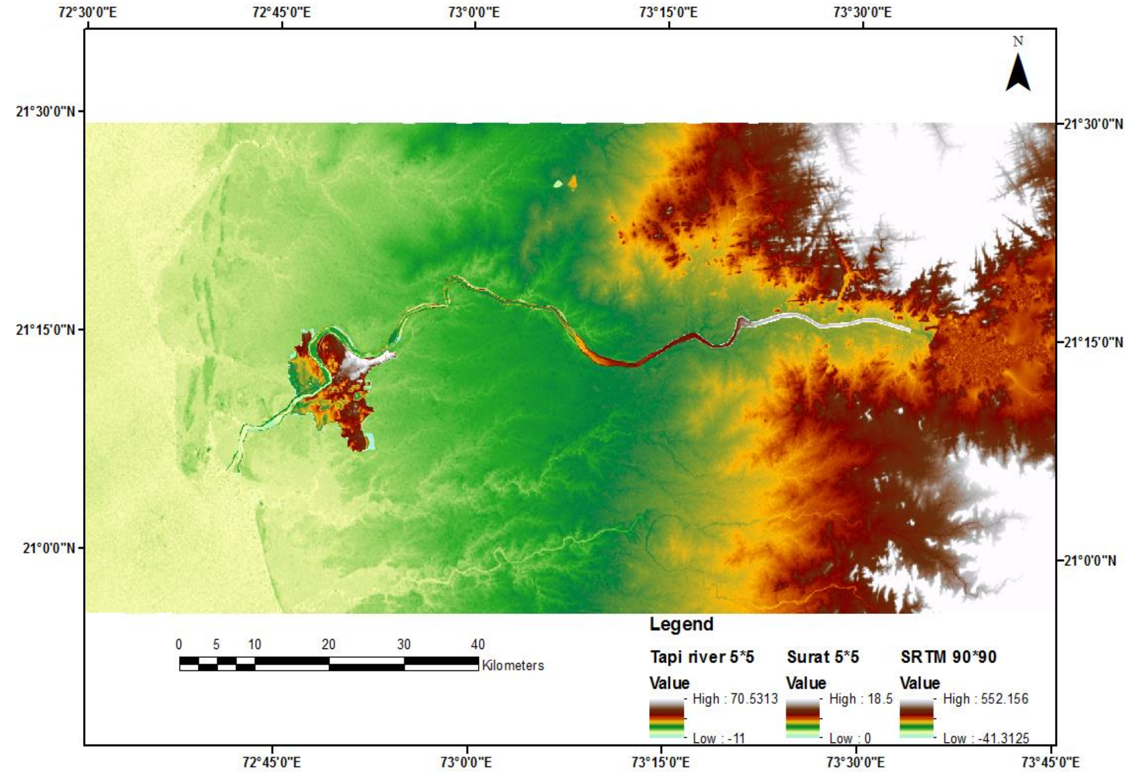
Fig. 4 a) Detail cross section of Retaining wall, b) Photograph of Retaining wall (Source: Surat Irrigation Circle (SIC), 2016)



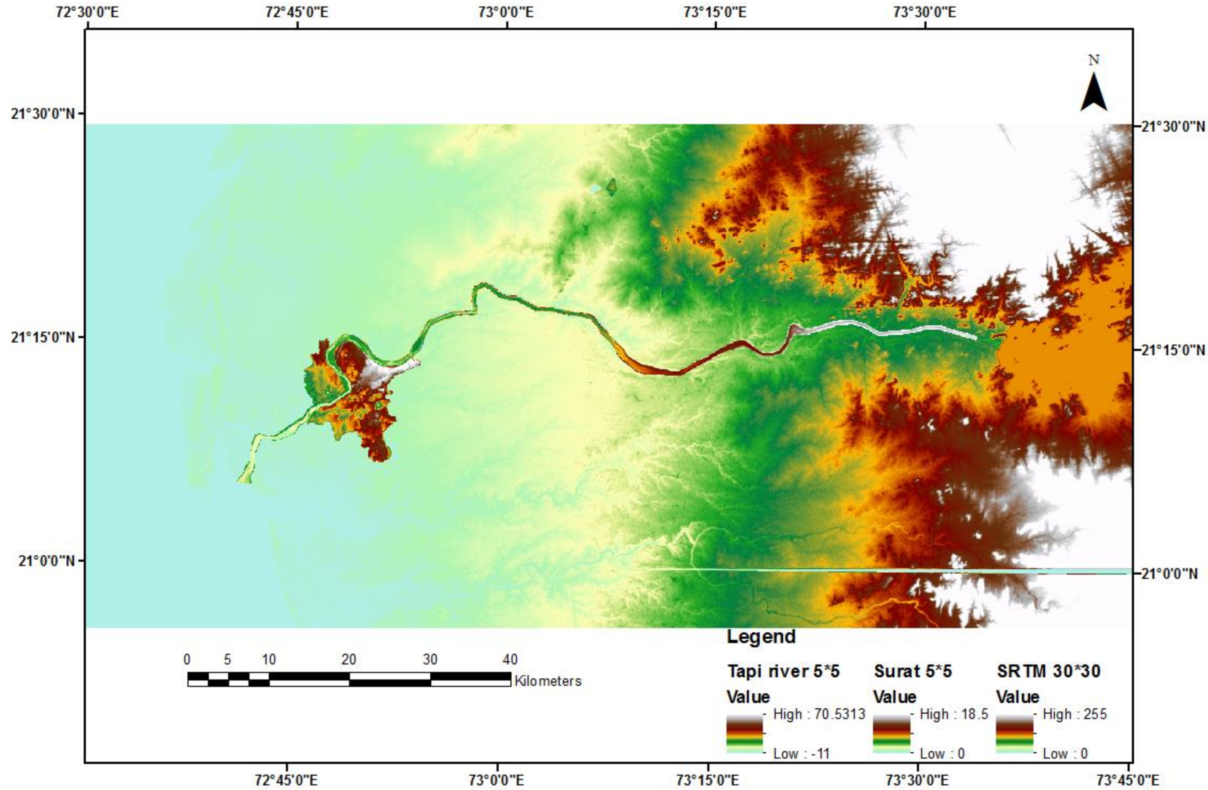
(a)

(b)

Fig. 5 a) Detail cross section of Earthen Embankment (Levees), b) Photograph of Levees (Source: Surat Irrigation Circle (SIC), 2016)



(a)



(b)

Fig. 6 a) DEM of Tapi river 5*5, Surat 5*5, SRTM 90*90 b) DEM of Tapi river 5*5, Surat 5*5, SRTM 30*30

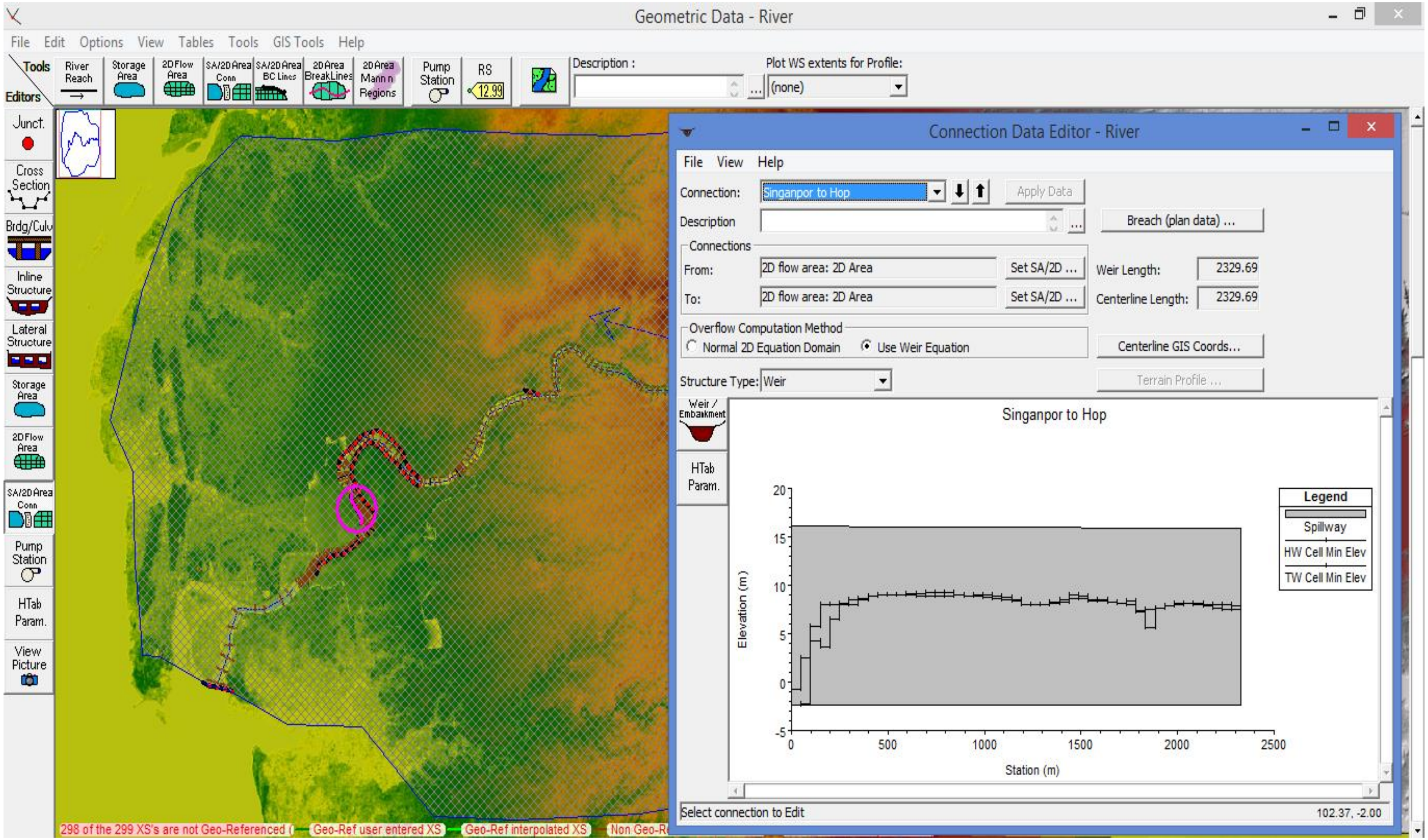
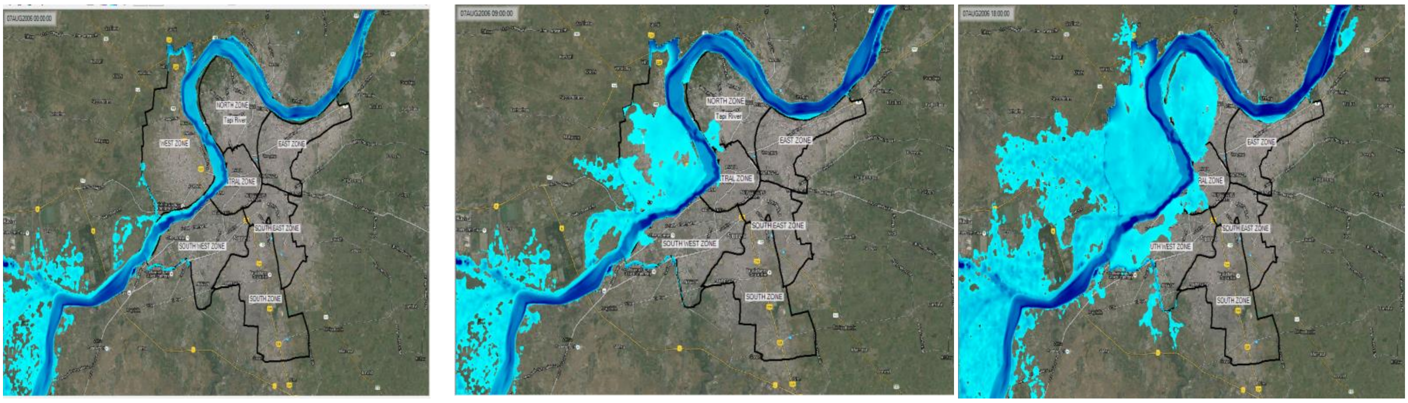
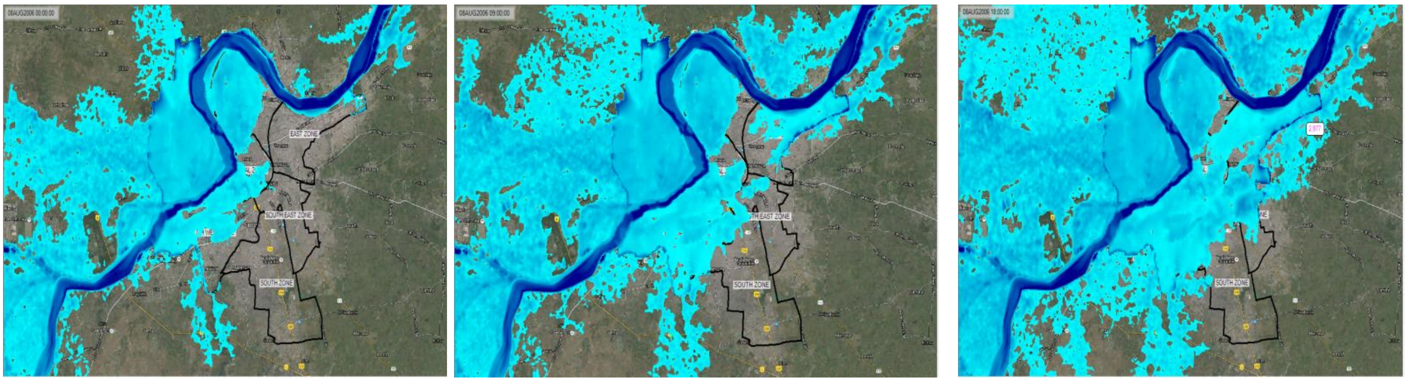


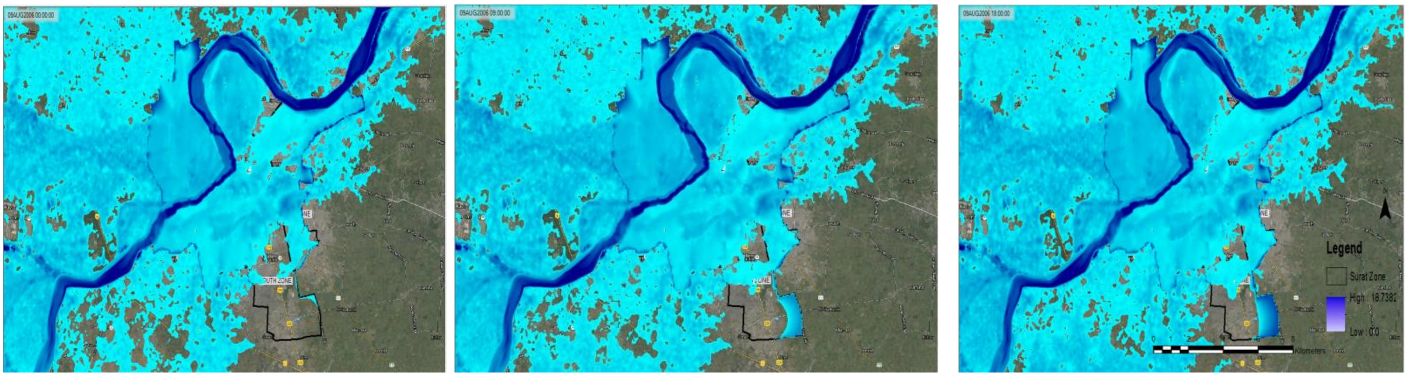
Fig. 7 HEC-RAS Geometry with levees structures.



7 Aug 2006 00, Ukai discharge : 9998m^3/s 7 Aug 2006 09, Ukai discharge : 14430m^3/s 7 Aug 2006 18, Ukai discharge : 23038m^3/s



8 Aug 2006 00, Ukai discharge : 23598m^3/s 8 Aug 2006 09, Ukai discharge : 23980m^3/s 8 Aug 2006 18, Ukai discharge : 25663m^3/s



9 Aug 2006 00 hrs, Ukai discharge : 25770m^3/s 9 Aug 2006 09, Ukai discharge : 21328m^3/s 9 Aug 2006 18, Ukai discharge : 18308m^3/s

Fig. 8 Simulated flood inundation of Surat city in 2006 corresponding the release from Ukai dam

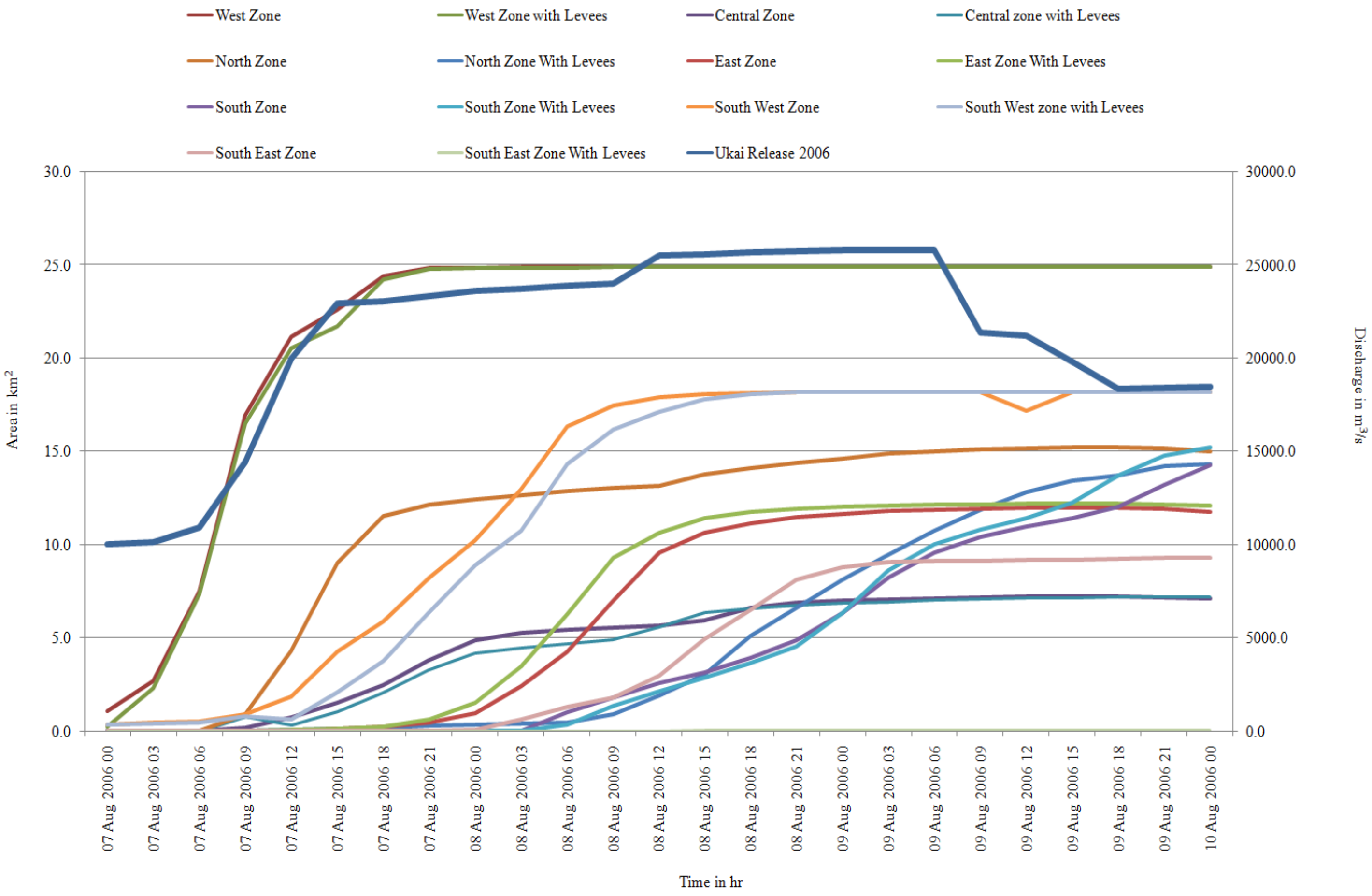


Fig. 9 Discharge-area inundation curve of different zone with and without levees.

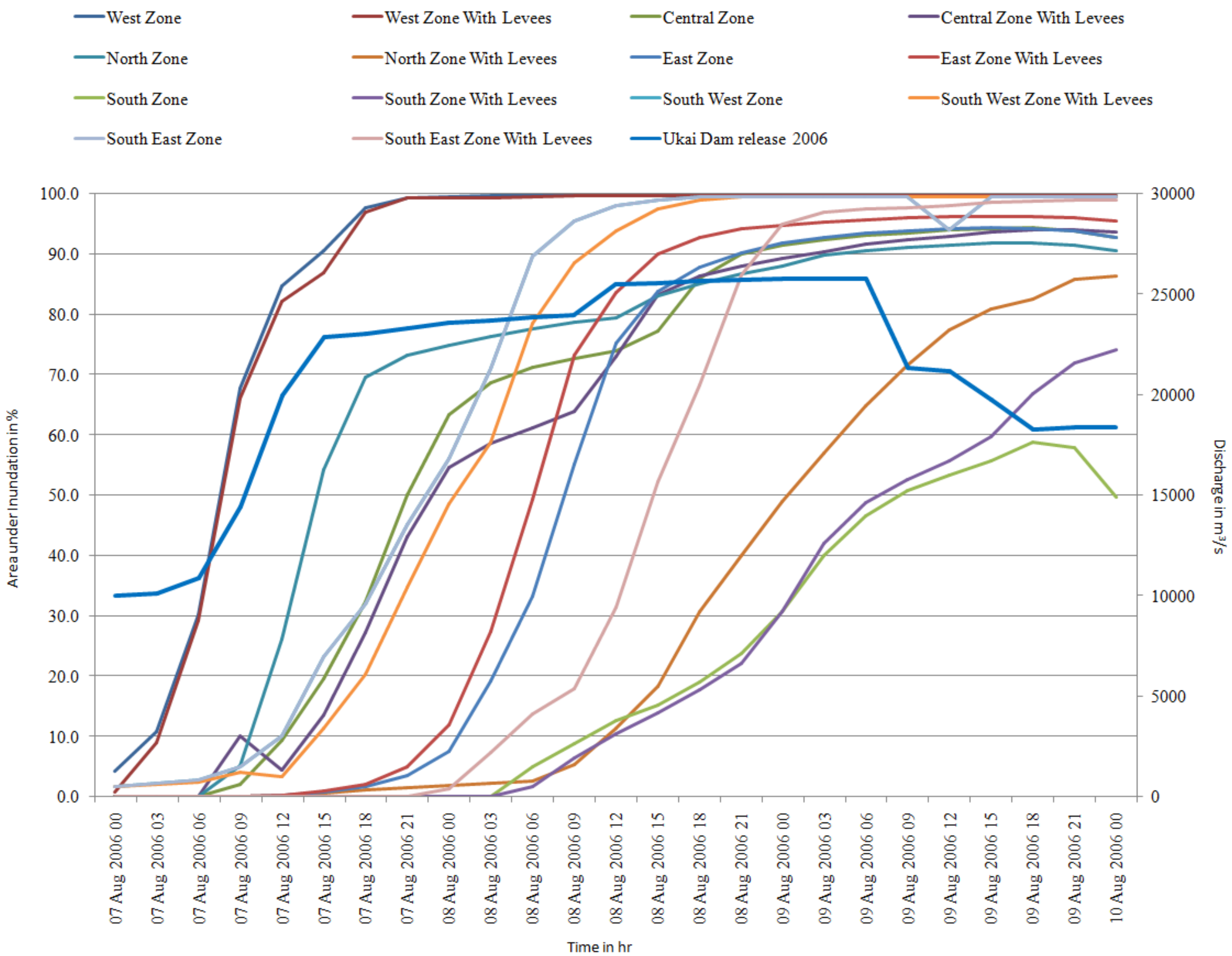


Fig. 10 Discharge-percentage area inundation curve of different zone with and without levees.

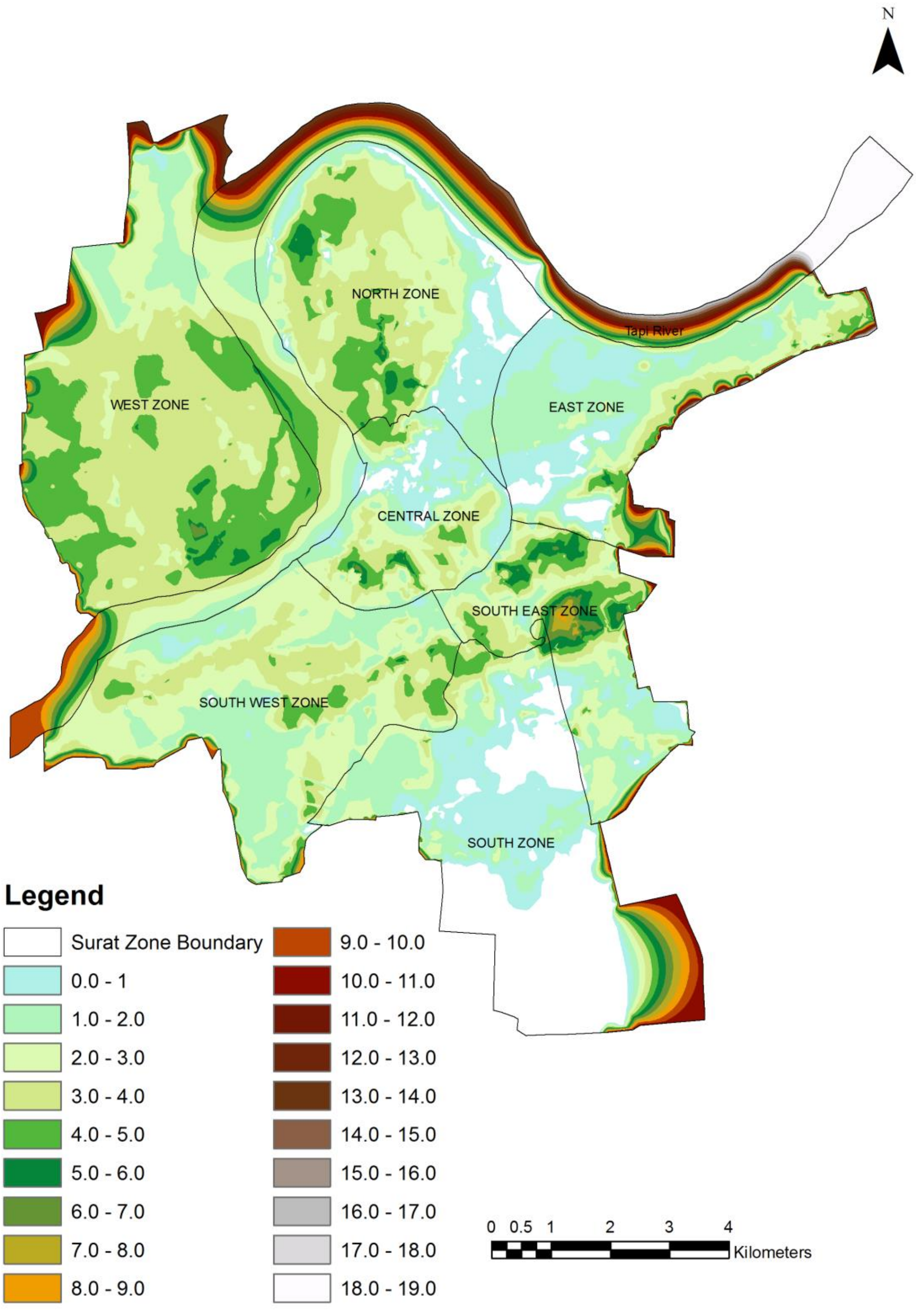


Fig. 11 Flood depth map of Surat city 9th August 18 hrs, 2006

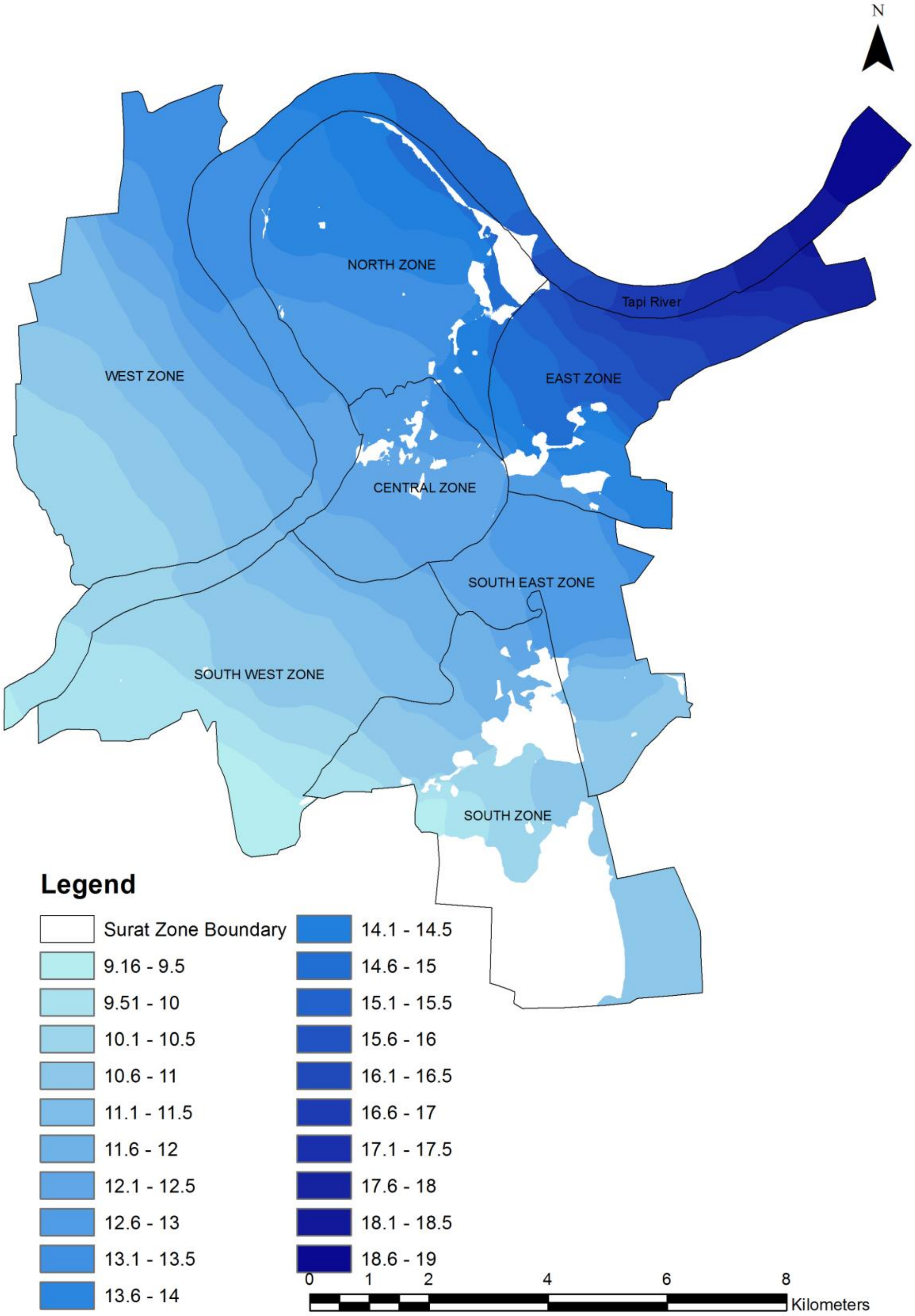


Fig. 12 Water Surface Elevation (WSE) map of Surat city, 9th August 18hrs 2006

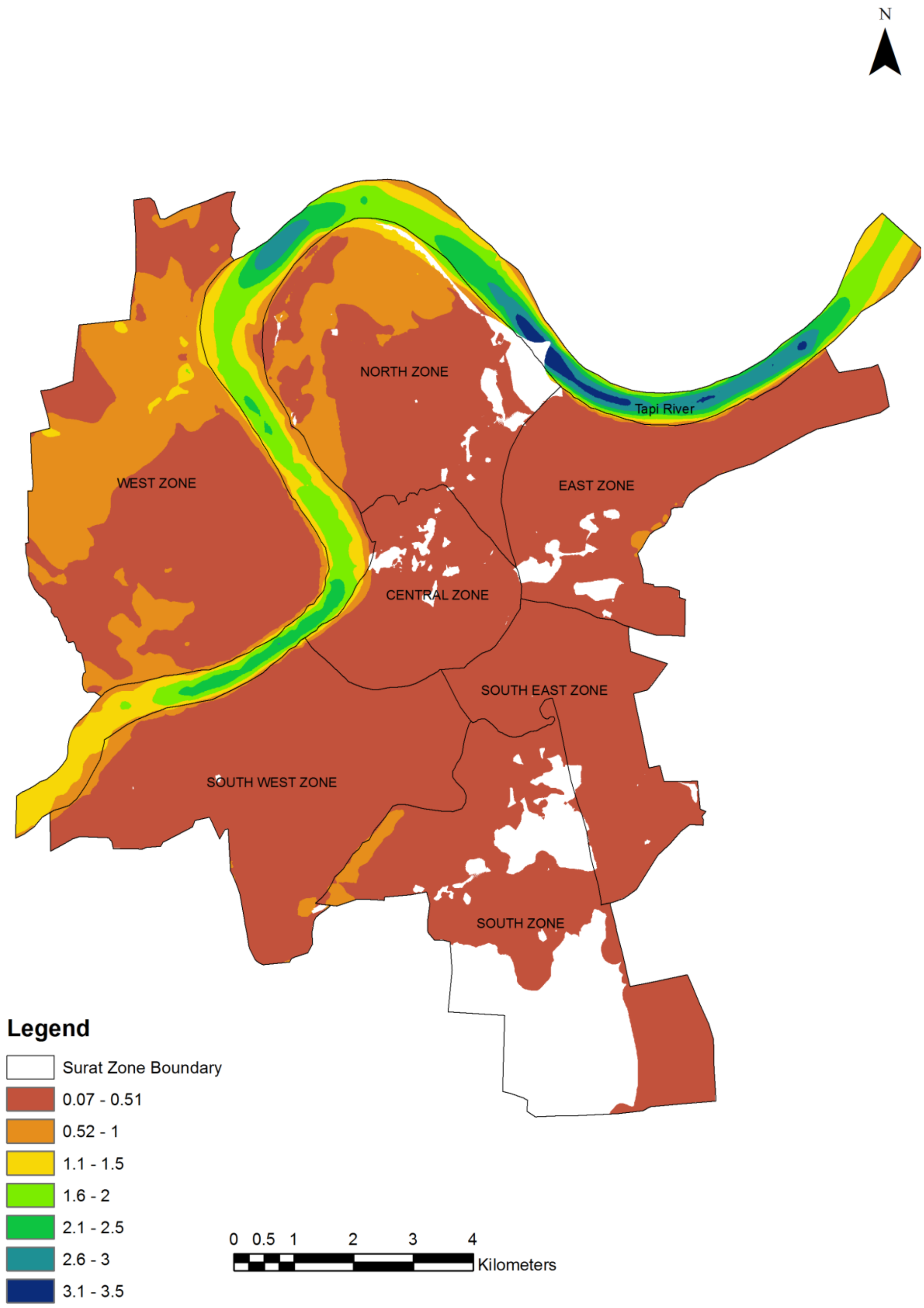


Fig. 13 Velocity distribution map of Surat city, 9th August 18 hrs 2006

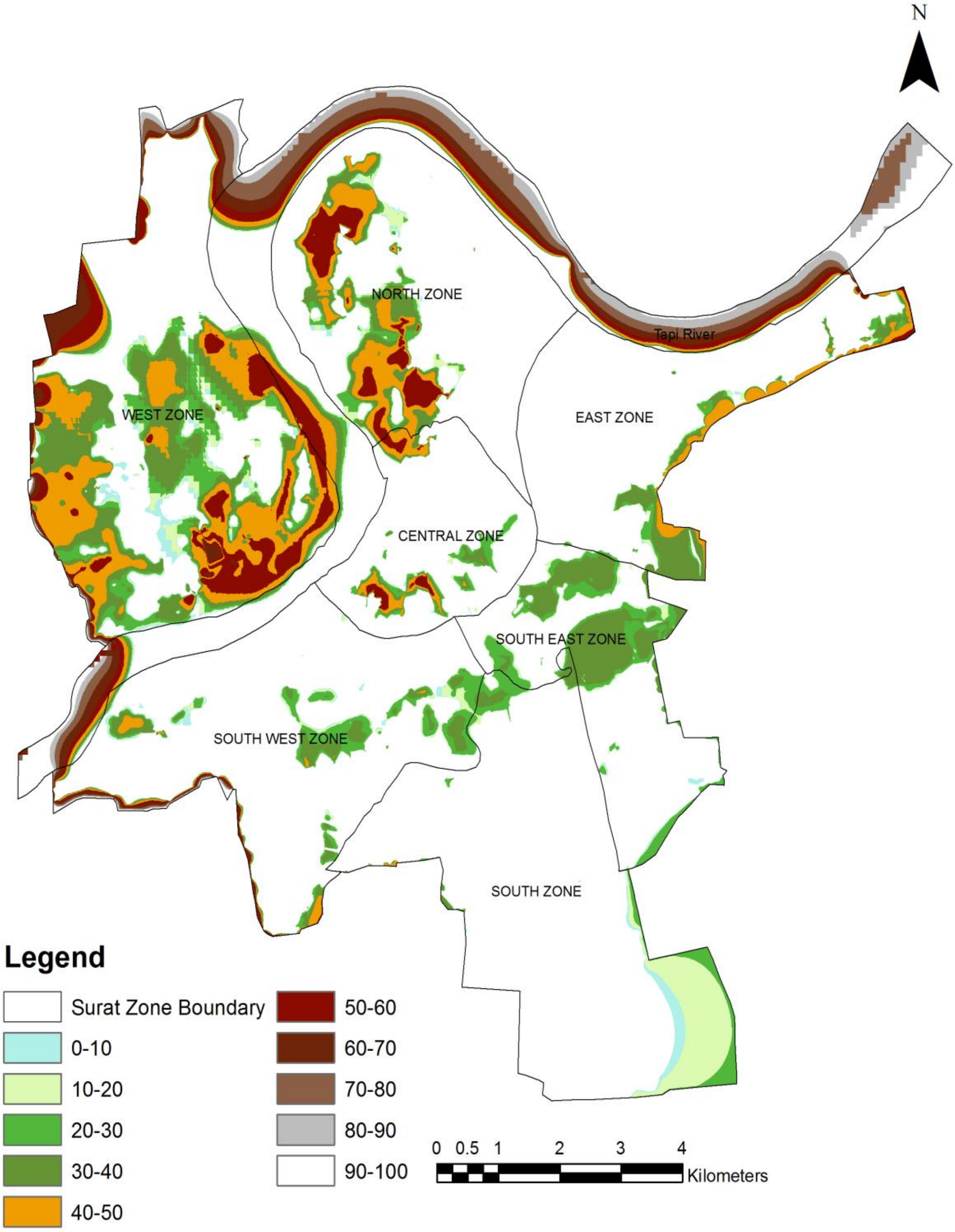


Fig. 14 Percentage time inundated map of Surat city.

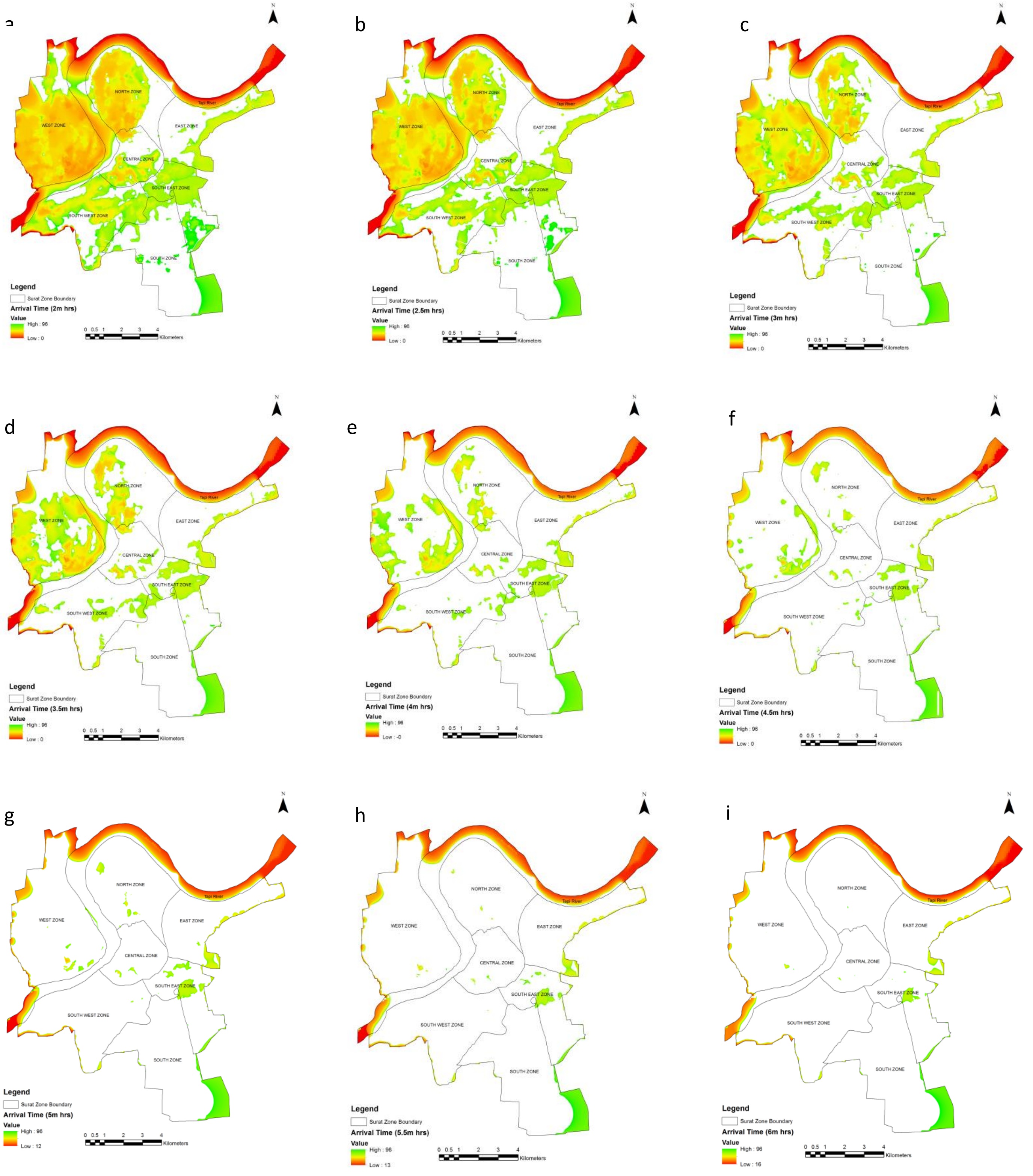


Fig.15 Flood arrival time in hrs., during depth of a) 2m b) 2.5m c) 3m d) 3.5m e)4m f) 4.5m g)5m h)5.5 m i) 6m

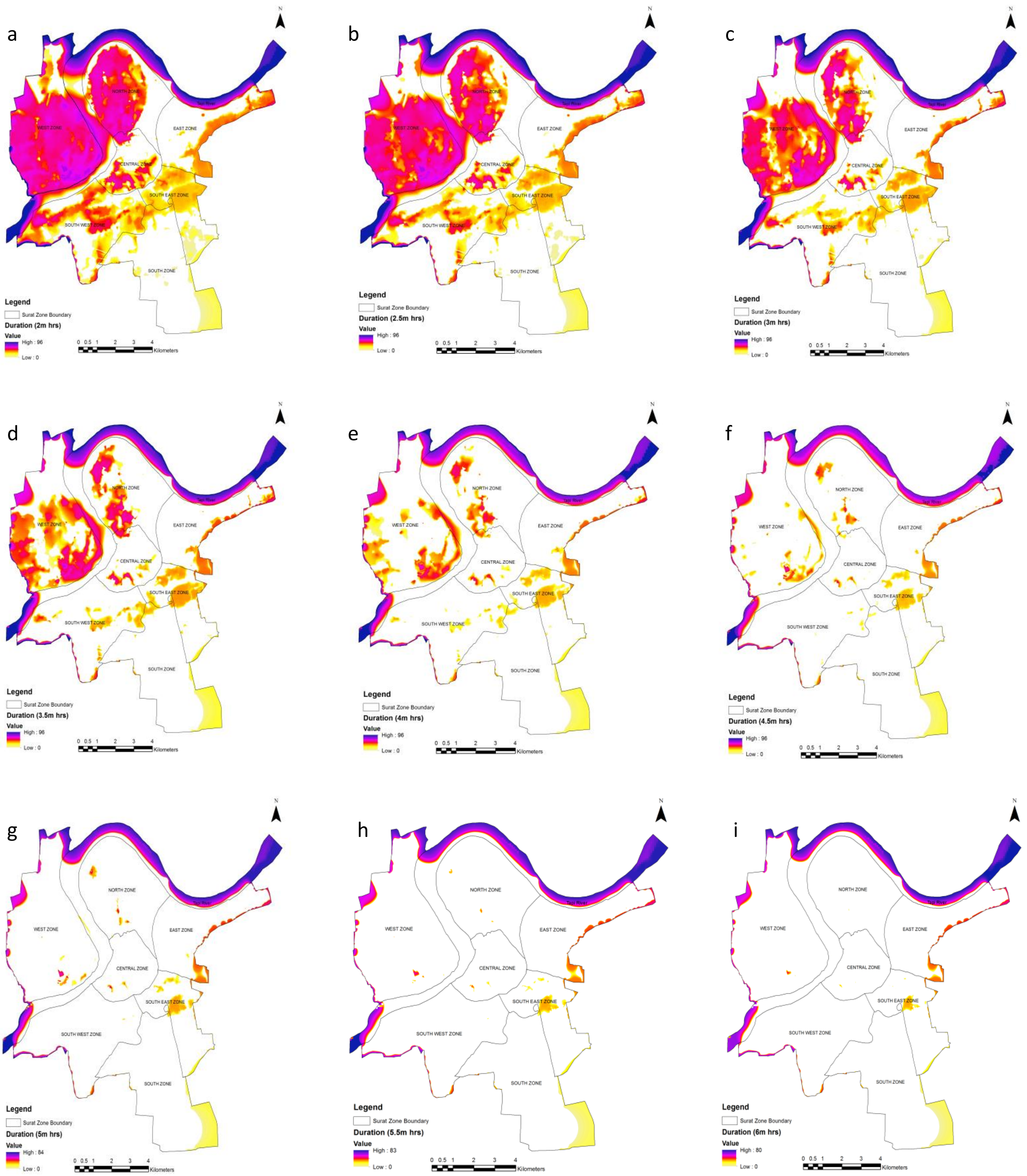


Fig. 16 Flood duration in hrs., during threshold flood depth of a) 2m b) 2.5m c) 3m d) 3.5m e)4m f) 4.5m g)5m h)5.5 m i) 6m

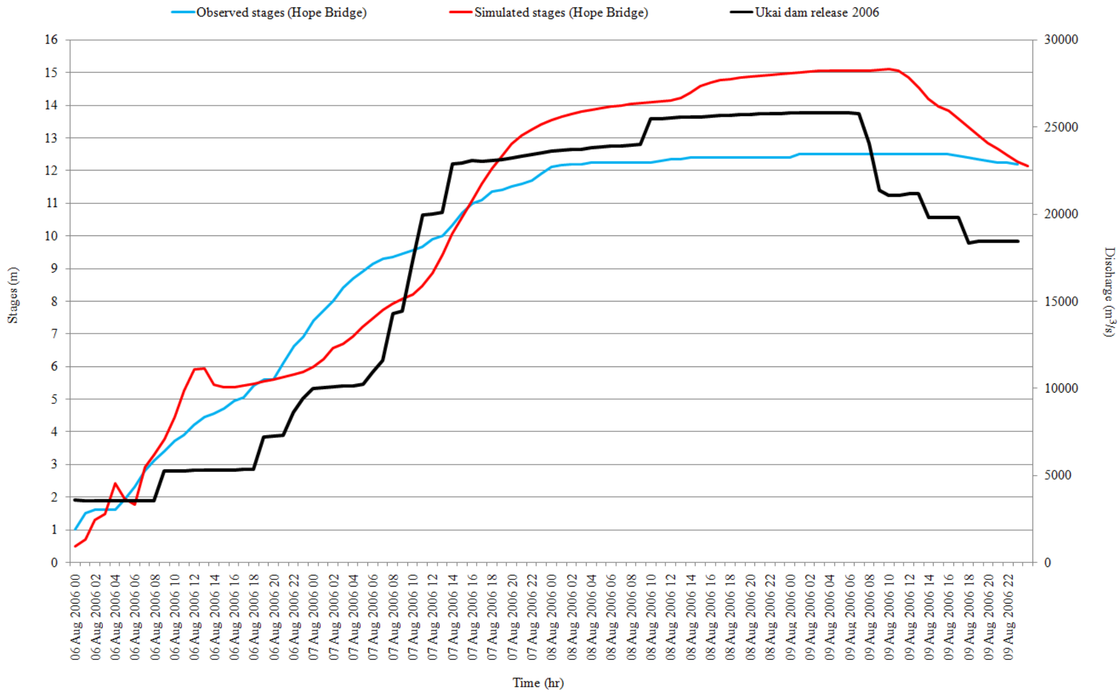


Fig. 17 Comparison of observed and simulated stages at Hope bridge, release from Ukai dam 2006

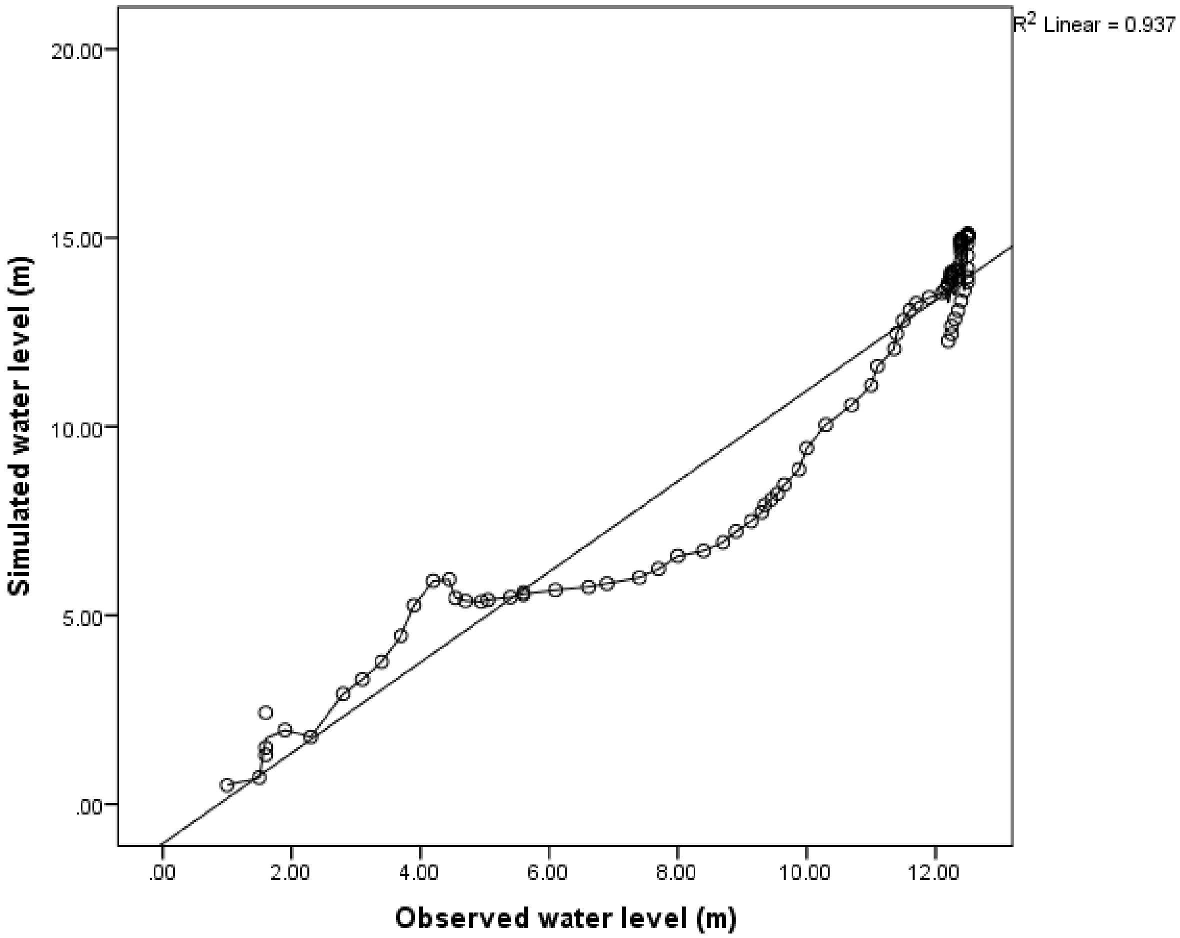


Fig. 18 Scatter plot of observed versus simulated water level at Nehru (Hope) Bridge

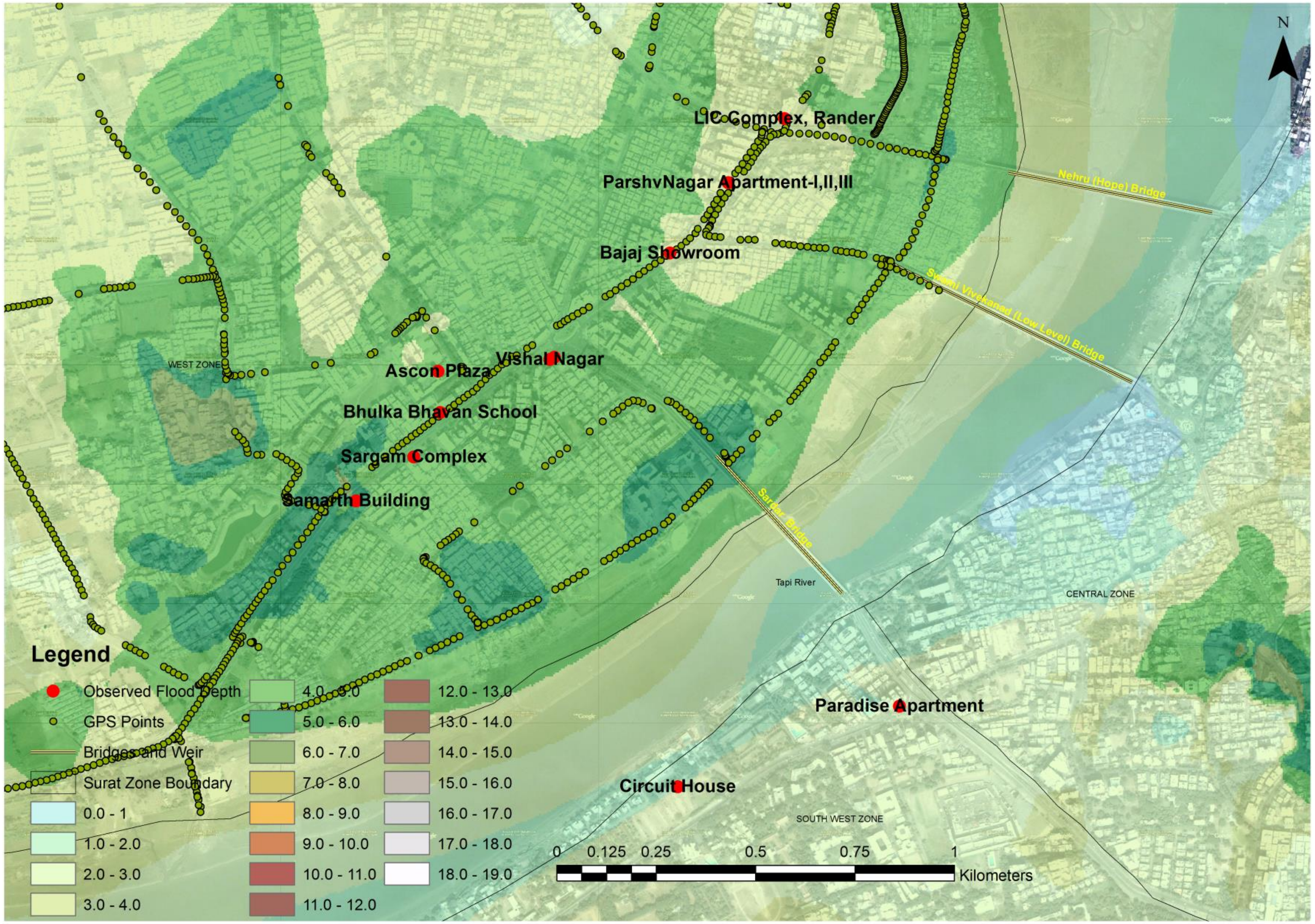


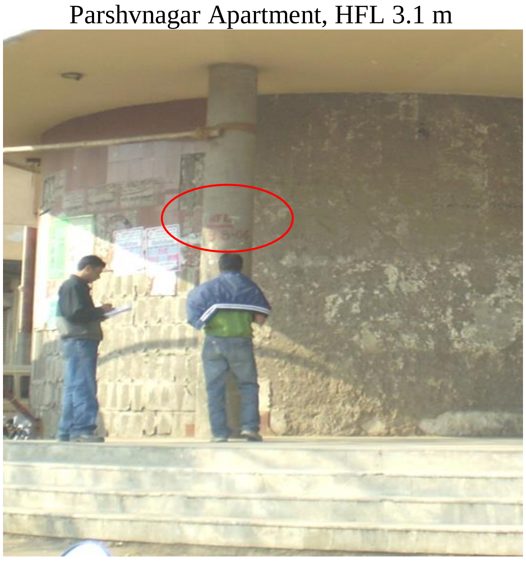
Fig. 19 Google earth image, Location points of observed flood depth, DGPS points and zone boundary overly map of simulated flood depth of 9th August 18 hrs 2006

Paradise Apartment, HFL 1.55 m,

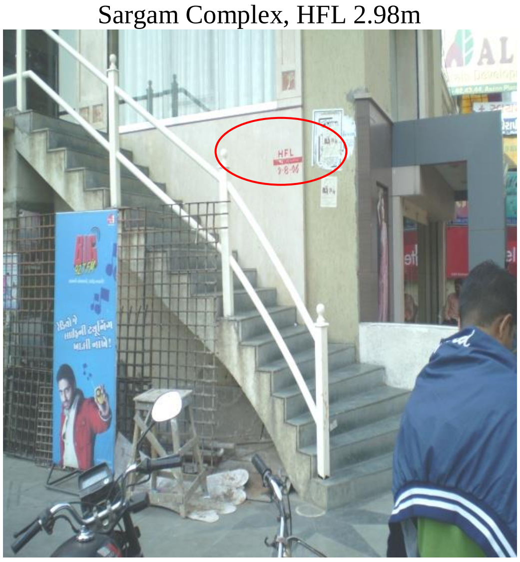
Circuit House, HFL 0.85m

Parshvnagar Apartment, HFL 3.1 m

Sargam Complex, HFL 2.98m



LIC Complex, 3.2m



Ascon Plaza, HFL 3.01m

Fig.20 Photograph shows the observed flood depth (indicated by red line) at 8th and 9th August 2006 at various places of Surat City

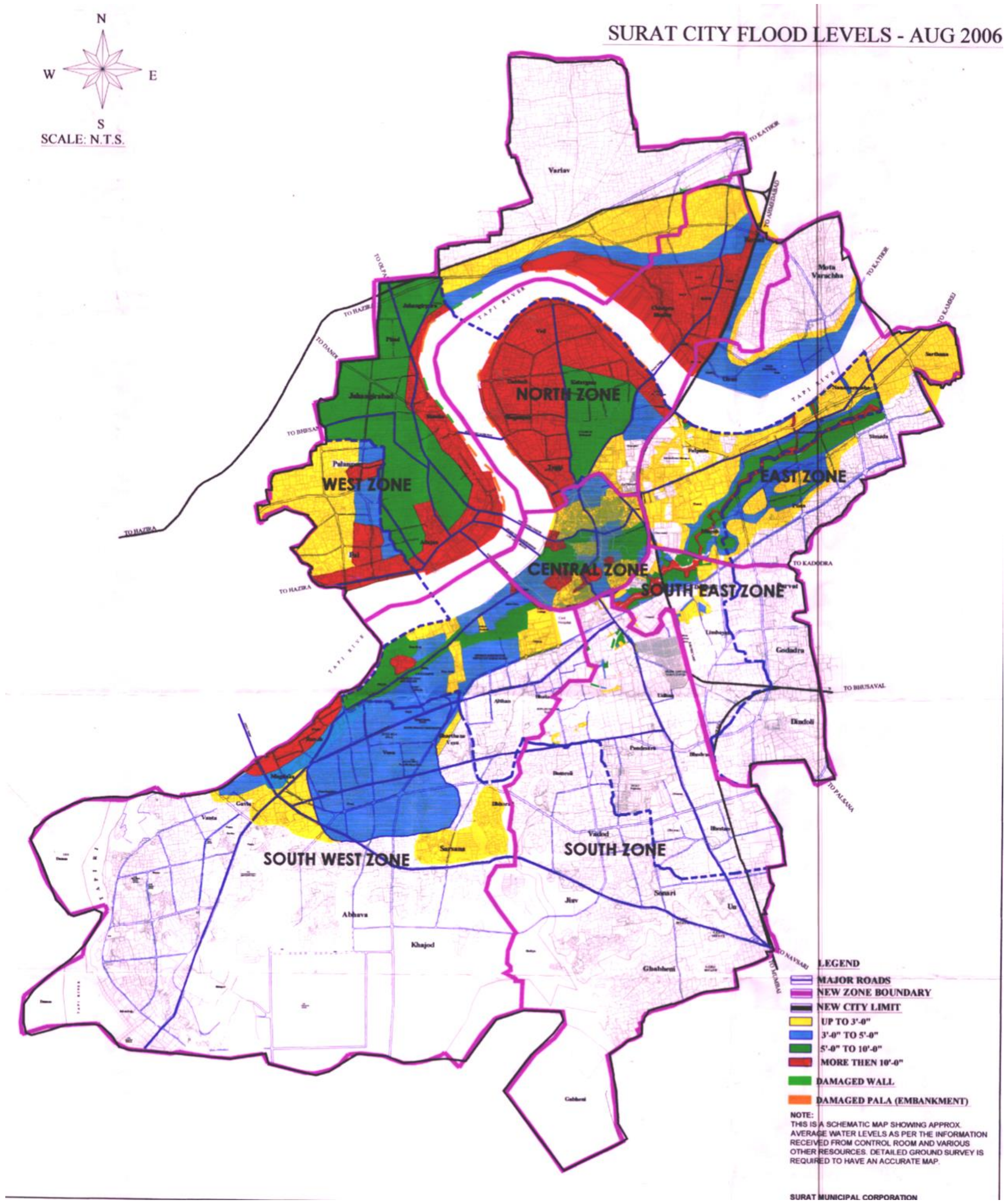
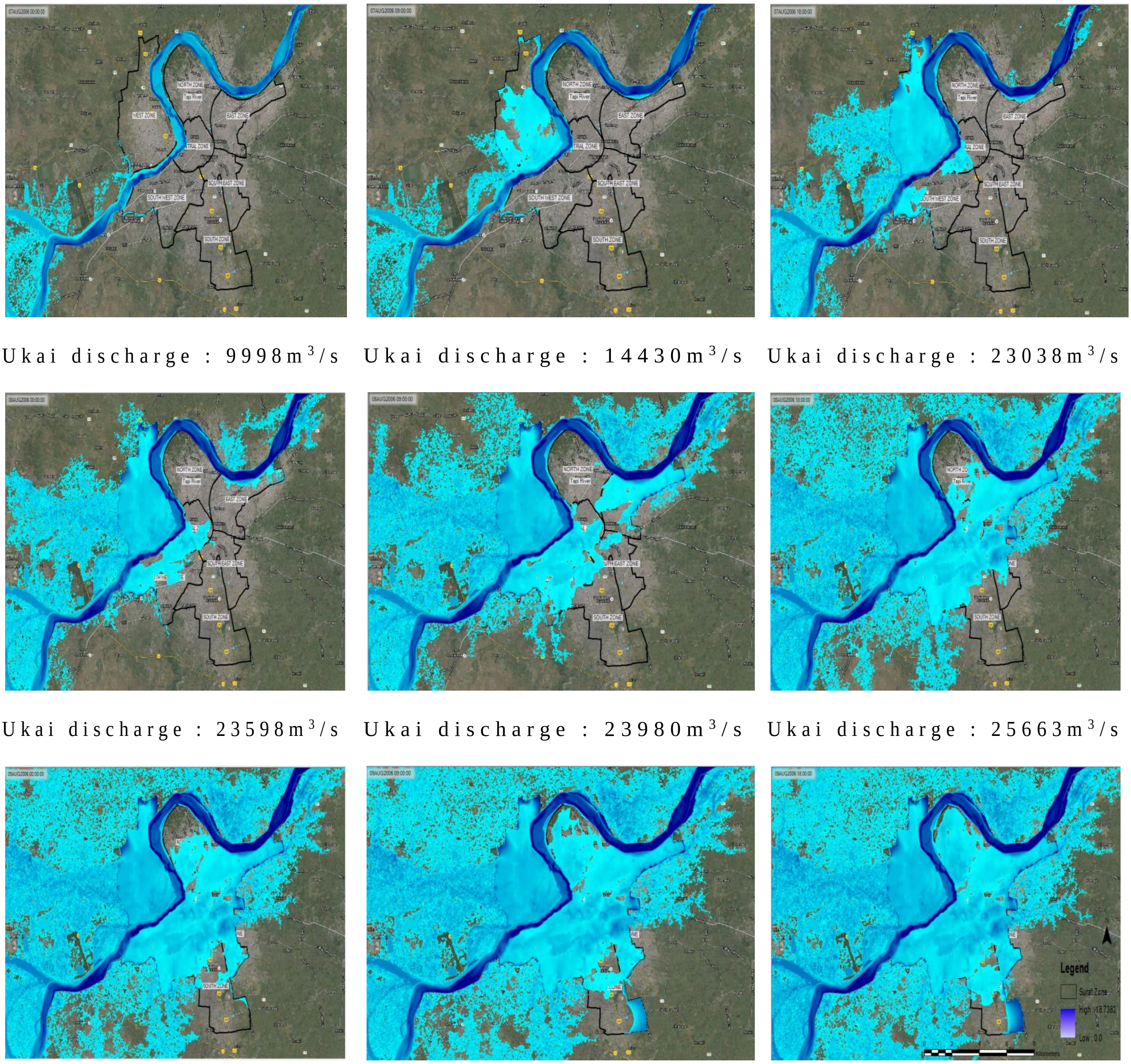


Fig. 21 Observed flood levels map of flood 2006, Surat city (Source: Surat Municipal Corporation (SMC)



Ukai discharge : 9998m^3/s Ukai discharge : 14430m^3/s Ukai discharge : 23038m^3/s

Ukai discharge : 23598m^3/s Ukai discharge : 23980m^3/s Ukai discharge : 25663m^3/s

Ukai discharge : 25770m^3/s Ukai discharge : 21328m^3/s Ukai discharge : 18308m^3/s

Fig. 22 Simulated flood inundation of Surat city with levees.


Left Bank of Tapi, d/s
of SVP Bridge

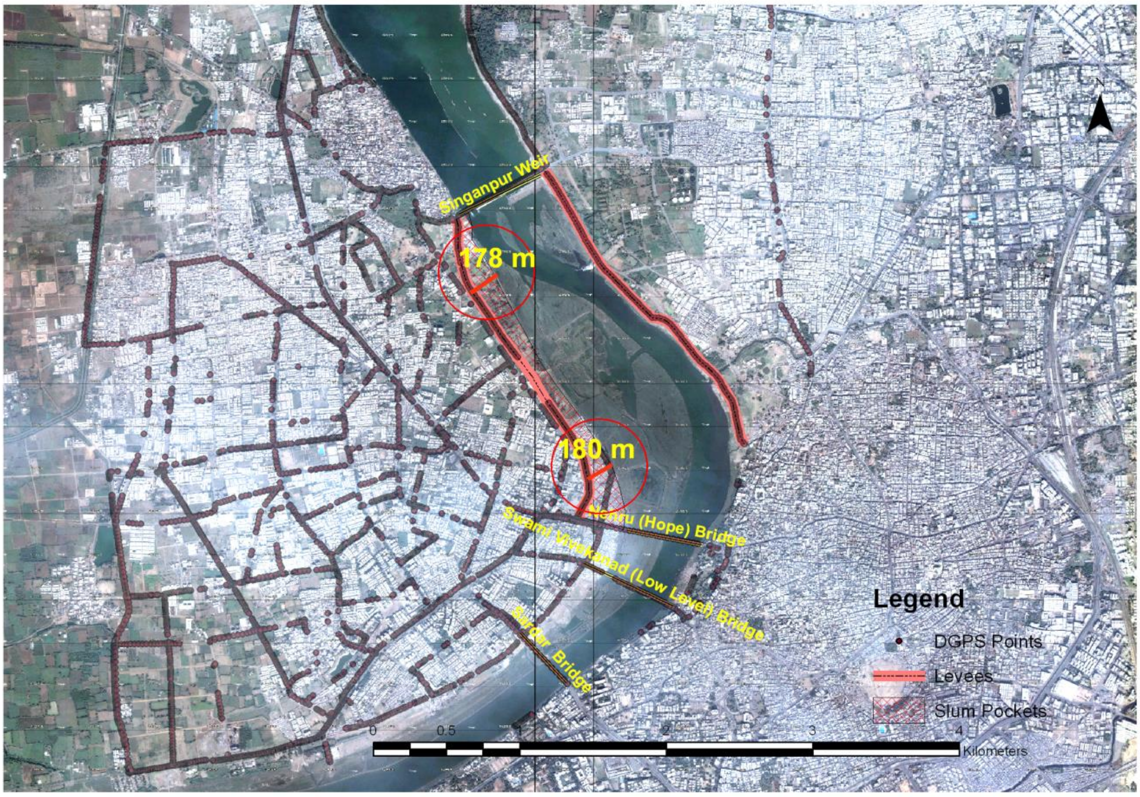
(a)


Right Bank of Tapi,
d/s of SVP Bridge

(b)

(c)

Fig. 23 a) Photograph shows flood retaining wall at d/s of SVP Bridge, left bank of river Tapi b) Photograph shows the bank protection work doesn't exist d/s of SVP bridge on the right bank of river Tapi c) Photograph Shows the construction just d/s of the levees.



(a)

(b)

Fig. 24 a) Photograph shows the position of right bank levees between Singanpur Weir and Nehru (Hope) Bridge b) Photograph shows the slum pockets are situated u/s of levees.

Table 1: Distance between different stations and average bed slope of Lower Tapi River.

Sr. No.	Station	Distance from Ukia dam (km)	Bed Slope Between stations	Bed Slope Ukai to Hop Bridge Hope Bridge to Sea
1	Ukai to Kakrapar Weir (L201-R201 to L155 - R155)	23.947	0.00014	
2	Kakrapar weir to Mandvi Gauge site (L155-R155 to L138-R138)	30.060	0.00670	
3	Mandvi Gauge site to Ghala Gauge site (L138-R138 to L76-R76)	64.943	0.00057	
4	Ghala Gauge site to Kathor Village (L76-R76 to L53-R53)	77.150	0.00066	0.00045
5	Kathor village to Railway Bridge (L53-R53 to L26-R26)	90.411	0.00011	
6	Railway Bridge to Singanpur weir (L26-R26 to L-6A – R-6A)	100.169	0.00006	
7	Singanpur weir to Hope bridge (L-6A – R-6A to LD26-RD26)	103.005	0.00050	
8	Hope Bridge to ONGC Bridge (LD26-RD26 to LD77-RD77)	112.436	0.00065	
9	ONGC Bridge to Left mouth of river to Arabian sea (LD77-RD77 to LD85-RD85)	116.468	0.00012	0.00001

Table 2 Details of Tapi bank protection work in Surat city

No	Name of Work	Length in (m).	Top R.L. in (m).	Left/Right Bank	Remarks
		Earthen Embankment			
1	Package No.1 Rander-Janghirpura	1560	16.41 - 16.55	Right Side	Completed
2	Package No.2			Right Side	Completed
	i) Janghirpura	925	16.55 – 16.84		
	ii) Amroli	335	17.43 – 19.30		
3	Package No. 3 Variyav	3552	16.84 - 17.20	Right Side	Completed
4	Package No. 4 Chhaparabhata	1800	17.20 – 17.43	Right Side	Completed
5	Package No. 5 Rander-Adajan	2336	16.10 – 15.83	Right Side	Completed
6	Package No. 6 Kathor- Amboli	1050	21.21 – 20.48	Right Side	Completed
7	Package No. 7 Singanpor	1430	16.12 – 16.36	Left Side	Completed
8	Package No. 8 Dabholi	1685	16.36 – 16.67	Left Side	Completed
9	Package No. 9 Ved	2500	16.77 – 17.20	Left Side	Completed
10	Package No. 10 Katargam	2550	17.20 – 17.56	Left Side	Completed
11	Village Tunki	535	16.00	Left Side	Completed
12	Coopers Bunglow Nr. Nehru Bridge	765	16.00	Left Side	Work in progress
13	Kapodra-Fulpada	1430	18.40	Left Side	Work in progress
14	Adajan	2970	10.65 – 9.65	Right Side	Work in progress
		Retaining Wall			
1	Amroli R.T. Wall	945	18.20	Right Side	Completed
2	Utran R.L. wall	385	18.20	Right Side	Completed
3	Fulpada	732	18.20	Left Side	Completed
4	Ash. Samshan	130	18.20	Left Side	Completed
5	Ashwani Kumar	616	18.20	Left Side	Completed
6	Vaidraj	171	18.20	Left Side	Completed
7	Old City wall	4840	18.20	Left Side	Completed

Table 3 Time, Ukai dam release and area under inundation in km^2 with and without levees structure.

Sr No	Date and Time	Release from Ukai in Cumecs	Release from Ukai in Lakh Cusecs	West Zone	West zone with Levee	Central Zone	Central zone with Levee	North Zone	North zone with Levee	East Zone	East zone with Levee	South Zone	South zone with Levee	South West Zone	South West zone with Levee	South East Zone	South East zone with Levee
1	07 Aug 2006 00	9997.79	353071.99	1.08	0.22	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.33	0.33	0.00	0.00
2	07 Aug 2006 03	10100.98	356716.11	2.72	2.27	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.42	0.39	0.00	0.00
3	07 Aug 2006 06	10905.69	385134.44	7.52	7.32	0.01	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.50	0.43	0.00	0.00
4	07 Aug 2006 09	14429.68	509584.15	16.94	16.51	0.16	0.78	0.87	0.02	0.01	0.01	0.00	0.00	0.91	0.75	0.00	0.00
5	07 Aug 2006 12	19974.46	705398.05	21.15	20.54	0.72	0.35	4.33	0.04	0.03	0.04	0.00	0.00	1.84	0.60	0.00	0.00
6	07 Aug 2006 15	22893.93	808499.14	22.61	21.69	1.49	1.04	8.99	0.10	0.10	0.11	0.00	0.00	4.25	2.07	0.00	0.00
7	07 Aug 2006 18	23038.09	813590.15	24.38	24.22	2.47	2.08	11.53	0.19	0.22	0.26	0.00	0.00	5.85	3.71	0.00	0.00
8	07 Aug 2006 21	23306.95	823084.94	24.81	24.79	3.82	3.30	12.13	0.27	0.45	0.62	0.00	0.00	8.23	6.36	0.01	0.01
9	08 Aug 2006 00	23597.62	833349.95	24.84	24.81	4.84	4.17	12.40	0.32	0.96	1.53	0.00	0.00	10.24	8.88	0.08	0.13
10	08 Aug 2006 03	23703.61	837092.99	24.88	24.83	5.24	4.47	12.64	0.38	2.44	3.48	0.00	0.01	12.97	10.73	0.64	0.70
11	08 Aug 2006 06	23876.6	843202.13	24.88	24.84	5.44	4.67	12.85	0.44	4.24	6.26	1.02	0.36	16.35	14.33	1.26	1.29
12	08 Aug 2006 09	23979.95	846851.93	24.88	24.88	5.55	4.87	13.02	0.90	7.01	9.30	1.80	1.32	17.44	16.17	1.82	1.70
13	08 Aug 2006 12	25499.5	900514.84	24.88	24.88	5.64	5.58	13.14	1.90	9.56	10.63	2.60	2.14	17.90	17.14	2.98	2.96
14	08 Aug 2006 15	25558.91	902612.91	24.88	24.88	5.90	6.36	13.76	3.03	10.65	11.43	3.11	2.87	18.07	17.80	4.95	4.94
15	08 Aug 2006 18	25662.66	906276.84	24.88	24.88	6.56	6.59	14.08	5.08	11.17	11.78	3.90	3.63	18.15	18.07	6.50	6.44
16	08 Aug 2006 21	25739.94	909005.98	24.88	24.88	6.86	6.72	14.37	6.62	11.47	11.96	4.89	4.55	18.17	18.16	8.12	8.16
17	09 Aug 2006 00	25770.01	910067.90	24.88	24.88	6.98	6.82	14.58	8.10	11.66	12.05	6.32	6.31	18.17	18.17	8.80	8.96
18	09 Aug 2006 03	25769.73	910058.01	24.88	24.88	7.05	6.90	14.87	9.44	11.79	12.12	8.22	8.61	18.17	18.17	9.09	9.15
19	09 Aug 2006 06	25770.01	910067.90	24.88	24.88	7.10	6.99	15.00	10.74	11.87	12.16	9.56	10.01	18.18	18.17	9.14	9.19
20	09 Aug 2006 09	21327.74	753189.14	24.88	24.88	7.14	7.05	15.08	11.86	11.92	12.19	10.40	10.78	18.18	18.17	9.17	9.21
21	09 Aug 2006 12	21169.98	747617.84	24.88	24.88	7.17	7.10	15.14	12.82	11.97	12.21	10.96	11.43	17.18	18.18	9.19	9.24
22	09 Aug 2006 15	19768.40	698121.05	24.88	24.88	7.19	7.14	15.21	13.39	11.99	12.23	11.41	12.24	18.18	18.18	9.22	9.31

23	09 Aug 2006 18	18307.83	646541.02	24.88	24.88	7.20	7.17	15.21	13.68	11.98	12.22	12.05	13.70	18.18	18.18	9.26	9.32
24	09 Aug 2006 21	18403.29	649912.19	24.88	24.88	7.17	7.18	15.13	14.20	11.91	12.19	13.23	14.75	18.18	18.18	9.31	9.33
25	10 Aug 2006 00	18417.47	650412.95	24.88	24.88	7.08	7.15	14.98	14.30	11.78	12.14	14.28	15.20	18.18	18.18	9.31	9.33

Table 4 Time, Ukai dam release and % area under inundation with and without levees structure

Sr No	Date and Time	Release from Ukai in Cumecs	Release from Ukai in Lakh Cusecs	West Zone %	West Zone % Levees	Central Zone%	Central Zone% Levees	North Zone%	North Zone% Levees	East Zone%	East Zone% Levees	South Zone%	South Zone% Levees	South West Zone%	South West Zone% Levees	South East Zone%	South East Zone% Levees
1	07 Aug 2006 00	9997.791	353071.99	4.32	0.86	0.00	0.0	0.00	0.0	0.06	0.06	0.0	0.0	1.8	1.79	1.8	0.00
2	07 Aug 2006 03	10100.98	356716.11	10.91	9.10	0.00	0.0	0.00	0.0	0.07	0.07	0.0	0.0	2.3	2.13	2.3	0.00
3	07 Aug 2006 06	10905.69	385134.44	30.12	29.32	0.07	0.1	0.02	0.0	0.08	0.08	0.0	0.0	2.7	2.38	2.7	0.00
4	07 Aug 2006 09	14429.68	509584.15	67.84	66.12	2.14	10.2	5.27	0.1	0.10	0.10	0.0	0.0	5.0	4.11	5.0	0.00
5	07 Aug 2006 12	19974.46	705398.05	84.70	82.24	9.44	4.5	26.16	0.3	0.27	0.30	0.0	0.0	10.1	3.30	10.1	0.00
6	07 Aug 2006 15	22893.93	808499.14	90.54	86.86	19.52	13.6	54.33	0.6	0.79	0.90	0.0	0.0	23.3	11.33	23.3	0.00
7	07 Aug 2006 18	23038.09	813590.15	97.63	96.99	32.34	27.2	69.66	1.1	1.70	2.04	0.0	0.0	32.1	20.34	32.1	0.00
8	07 Aug 2006 21	23306.95	823084.94	99.35	99.28	50.04	43.2	73.29	1.6	3.57	4.92	0.0	0.0	45.1	34.83	45.1	0.11
9	08 Aug 2006 00	23597.62	833349.95	99.48	99.37	63.48	54.7	74.95	1.9	7.56	12.02	0.0	0.0	56.1	48.67	56.1	1.37
10	08 Aug 2006 03	23703.61	837092.99	99.65	99.44	68.69	58.6	76.39	2.3	19.22	27.40	0.0	0.1	71.1	58.78	71.1	7.38
11	08 Aug 2006 06	23876.6	843202.13	99.65	99.50	71.28	61.2	77.63	2.7	33.36	49.30	5.0	1.7	89.6	78.53	89.6	13.69
12	08 Aug 2006 09	23979.95	846851.93	99.65	99.64	72.73	63.9	78.65	5.4	55.17	73.25	8.8	6.4	95.6	88.60	95.6	18.05
13	08 Aug 2006 12	25499.5	900514.84	99.65	99.65	73.93	73.1	79.40	11.5	75.30	83.71	12.7	10.5	98.1	93.90	98.1	31.42
14	08 Aug 2006 15	25558.91	902612.91	99.65	99.65	77.32	83.3	83.16	18.3	83.82	90.00	15.2	14.0	99.0	97.55	99.0	52.34
15	08 Aug 2006 18	25662.66	906276.84	99.65	99.65	86.00	86.4	85.10	30.7	87.94	92.77	19.0	17.7	99.5	98.99	99.5	68.25
16	08 Aug 2006 21	25739.94	909005.98	99.65	99.65	89.95	88.1	86.83	40.0	90.30	94.20	23.9	22.2	99.6	99.49	99.6	86.52
17	09 Aug 2006 00	25770.01	910067.90	99.65	99.65	91.48	89.4	88.12	49.0	91.80	94.88	30.8	30.8	99.6	99.56	99.6	95.00
18	09 Aug 2006 03	25769.73	910058.01	99.65	99.65	92.37	90.4	89.83	57.1	92.85	95.41	40.1	42.0	99.6	99.58	99.6	97.03
19	09 Aug 2006 06	25770.01	910067.90	99.65	99.65	93.06	91.6	90.64	64.9	93.45	95.73	46.6	48.8	99.6	99.58	99.6	97.46
20	09 Aug 2006 09	21327.74	753189.14	99.65	99.65	93.54	92.4	91.11	71.7	93.88	95.98	50.7	52.6	99.6	99.59	99.6	97.71
21	09 Aug 2006 12	21169.98	747617.84	99.65	99.65	94.00	93.1	91.49	77.5	94.24	96.16	53.4	55.7	94.1	99.59	94.1	97.99
22	09 Aug 2006 15	19768.40	698121.05	99.65	99.65	94.29	93.6	91.92	80.9	94.38	96.27	55.7	59.7	99.6	99.60	99.6	98.68

23	09 Aug 2006 18	18307.83	646541.02	99.65	99.65	94.35	94.0	91.90	82.7	94.31	96.24	58.8	66.8	99.6	99.61	99.6	98.86
24	09 Aug 2006 21	18403.29	649912.19	99.65	99.65	93.92	94.1	91.41	85.8	93.80	95.99	57.9	71.9	99.6	99.61	99.6	98.92
25	10 Aug 2006 00	18417.47	650412.95	99.65	99.65	92.78	93.8	90.52	86.4	92.77	95.56	49.8	74.2	99.6	99.61	99.6	98.91